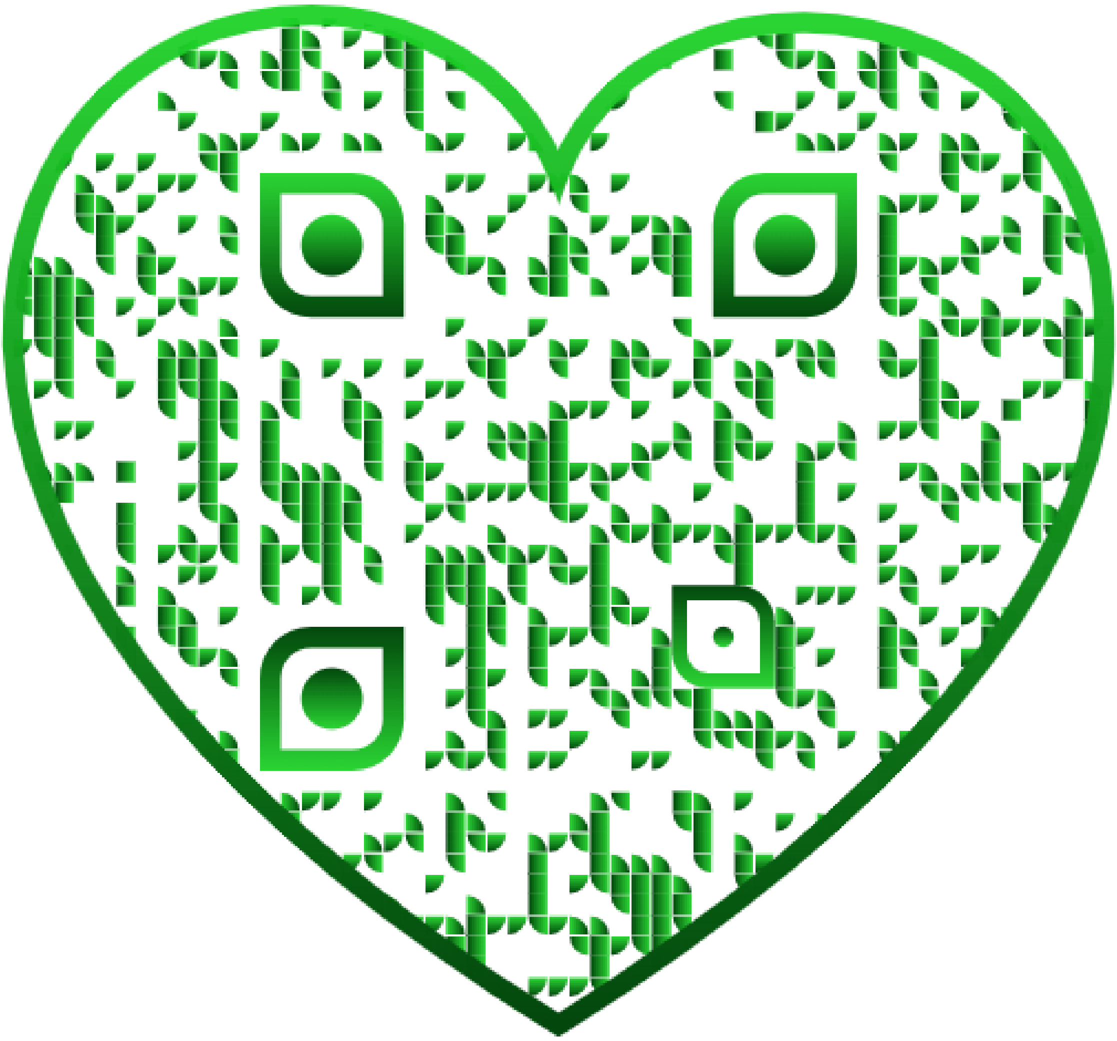
BBC
Sky at Night
MAGAZINE
DISCOVER SPACE
COLLECTION

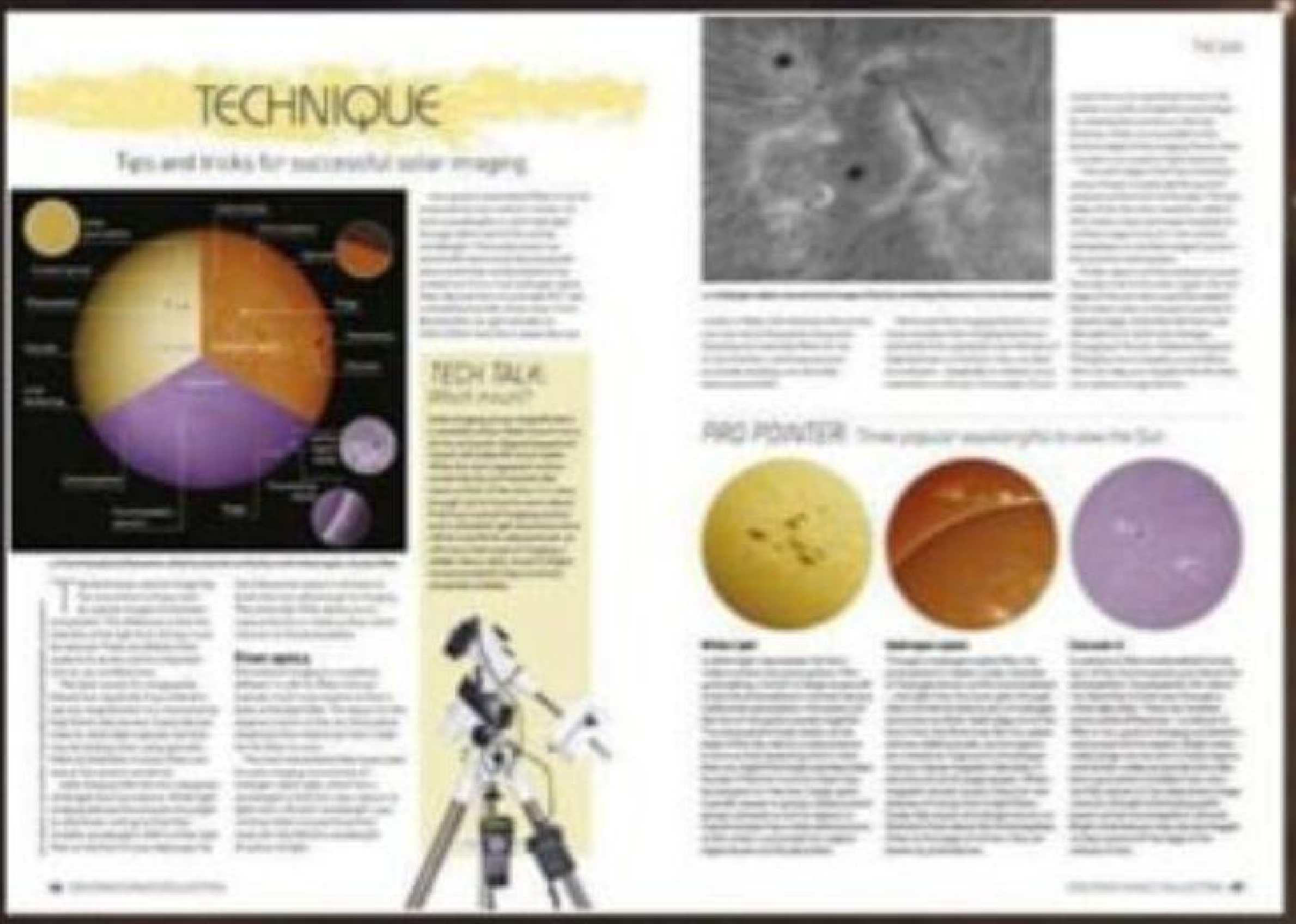
THE GUIDE TO THE UNIVERSE

An illustrated voyage across space, from the Sun to the edge of the cosmos

By Mark A Garlick



MASTERCLASS 3


TECHNIQUE

THE DEEP SKY

SOLAR SYSTEM OBJECTS BASIC TECHNIQUES

IMAGE BUILDING

TAKE YOUR ASTRO IMAGING TO THE NEXT LEVEL

SPECIAL EDITION

BBC Sky at Night MAGAZINE DISCOVER SPACE COLLECTION

The Complete Guide to ASTRO PHOTOGRAPHY

Photograph the Moon, meteors and Milky Way

Expert processing tips to enhance your photos

Create short films from your still shots

Night sky targets for your smartphone

Capture the dynamic nature of our Sun

The right kit for imaging stars, planets and more

ONLY £9.99 INC P&P*

FROM THE MAKERS OF BBC Sky at Night MAGAZINE

The Complete Guide to ASTRO PHOTOGRAPHY

New and updated, *The Complete Guide to Astrophotography* is packed with essential advice and illustrated instructions that will give you everything you need to know about imaging the night sky. From beginner's shots with a smartphone to image processing tips for seasoned deep-sky imagers, there's something for everyone.

Plus – subscribers to *BBC Sky at Night Magazine* receive FREE UK delivery on this special edition.

ORDER YOUR COPY TODAY

www.buysubscriptions.com/astrophotography

Alternatively call 03330 162138† and quote 'The Complete Guide to Astrophotography PRINT1'

†Calls from landlines will cost up to 9p per minute. Call charges from mobile phones will cost between 3p and 55p per minute but are included in free call packages.
Lines are open 8am–6pm weekdays and 9am–1pm Saturday for orders only.
*Subscribers to *BBC Sky at Night Magazine* receive FREE UK POSTAGE on this special edition. Prices including postage are: £11.49 for all non-subscribers, £12.99 for Europe and £13.49 for the Rest of World.
All orders subject to availability. Please allow up to 21 days for delivery.

IMMEDIATE
MEDIA Co

EDITORIAL
Author and Illustrator Mark A Garlick
Editor Chris Bramley
Art Editor Steve Marsh
Production Editor Robert Banino, Jane Williamson

CIRCULATION & ADVERTISING
Head of Circulation Rob Brock
Advertising Manager
Sam Jones +44 (0)117 300 8145

PRODUCTION
Production Director Sarah Powell
Production Coordinator Derrick Andrews
Reprographics Tony Hunt and Chris Sutch

PUBLISHING
Publisher Jemima Dixon
Managing Director Andy Healy
CEO Tom Bureau

BBC STUDIOS, UK PUBLISHING
Chair, Editorial Review Boards
Nicholas Brett
Managing Director, Consumer Products and Licensing Stephen Davies
Head of Publishing Mandy Thwaites
Compliance Manager Cameron McEwan
UK Publishing Coordinator Eva Abramik
uk.publishing@bbc.com; www.bbcstudios.com

© Immediate Media Company Bristol 2019. All rights reserved. No part of *The Guide to the Universe* may be reproduced in any form or by any means either wholly or in part, without prior written permission of the publisher. Not to be resold, lent, hired out or otherwise disposed of by way of trade at more than the recommended retail price or in mutilated condition. Printed in the UK by William Gibbons Ltd. The publisher, editor and authors accept no responsibility in respect of any products, goods or services which may be advertised or referred to in this issue or for any errors, omissions, misstatements or mistakes in any such advertisements or references.

Revised, updated and abridged from *Cosmic Menagerie*, first published by Red Lemon Press, 2013

MIX
FSC® C015156
recycle

We abide by IPSO's rules and regulations. To give feedback about our magazines, please visit immediate.co.uk, email **editorialcomplaints@immediate.co.uk** or write to The Editor, *BBC Sky at Night Magazine*, Immediate Media Co., Eagle House, Colston Avenue, Bristol BS1 4ST

Like what you've read?

Email us at:
contactus@skyatnightmagazine.com

COVER IMAGE: MARK GARLICK

Scan the QR codes where you see them to watch animations

Welcome

Consider the stars. They may all look the same in the night sky, but looks can be deceiving. They, in fact, come in many different varieties, ranging from swollen, gargantuan red supergiants – hundreds of times larger than the Sun – to puny neutron stars, as massive as the Sun and yet, incredibly, no larger than London.

How many different stars are out there, what do they look like, how do they compare, how did they come to be? *The Guide to the Universe* has the answers. It had been designed so that you can flick through its five sections and find descriptions – alongside full-page artworks and, occasionally, animations – of all the various kinds of astronomical phenomena there are. Crucially, though, *The Guide to the Universe* is not an encyclopaedia or a work of reference. Instead it provides an introduction and illustration for each astronomical phenomenon before moving on to the next – a move that usually involves jumping up a step in terms of scale, which, in astronomical terms, very quickly leads to objects that stretch over unimaginably vast distances.

But why rely on artwork instead of photographs? There is a good reason for this. True, the telescopes astronomers use can and do produce staggering imagery of the cosmos we live in. Photographs taken by the Hubble Space Telescope have enthralled us for almost three decades. Yet despite the power of such instruments there are limits to what they can show. If you wish to witness a magnetic star from the landscape of an alien planet, or float among the particles in Saturn's rings, or examine a binary star at a range close enough to resolve the two members, or catch protoplanets colliding in the juvenile Solar System, you'll either need the help of technology that's yet to be invented or the eyes and hands of an artist. This is where *The Guide to the Universe* comes in. So sit back and enjoy the ride!

Mark A Garlick,
Author and Illustrator

Dr Mark A Garlick is a former astronomer. He holds a PhD in interacting binary stars from the UK's Mullard Space Science Laboratory in Surrey. He is a Fellow of the International Association of Astronomical Artists and currently works as a freelance writer, illustrator and computer animator.

MARK GARLICK

Contents

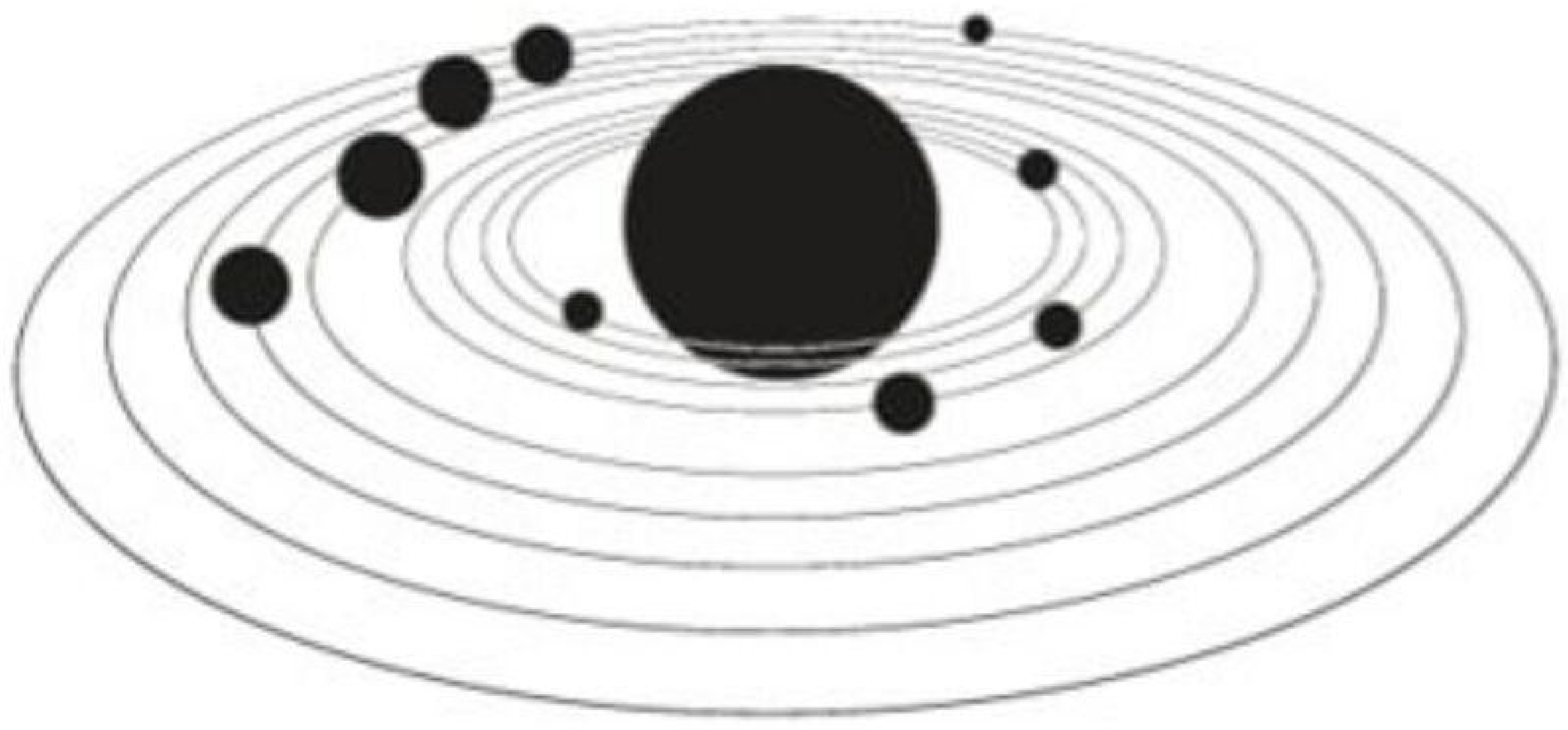
6 Planets and related specimens
8 Planetary formation
10 Gas giants
12 Ice giants
14 Terrestrial planets
16 Asteroids
18 Dwarf planets
20 Satellites and rings
22 Comets and comet clouds
24 Extrasolar planets

26 The stellar zoo
28 Protostars: young stellar objects
30 T Tauri stars: stellar adolescents
32 Main sequence stars: nuclear powerhouses
34 Red dwarfs: feeble and faint
36 Subgiants: growing old
38 Giants: geriatric stars
40 Supergiants: luminous powerhouses
42 White and black dwarfs: stellar corpses
44 Neutron stars and pulsars: the ultimate destiny
46 Black holes: light traps
48 Brown dwarfs: failed stars

50 Camaraderie of the stars
52 Wide binaries
54 Novae
56 Dwarf novae
58 Intermediate polars
60 Polars
62 Low-mass X-ray binaries
64 High-mass X-ray binaries
66 Microquasars
68 Algol systems
70 Overcontact binaries
72 Multiple systems
74 Open clusters
76 Globular clusters

78 Interstellar fog
80 Molecular clouds: stellar nurseries
82 Protoplanetary discs: planetary nurseries
84 Herbig-Haro objects: stellar shockwaves
86 Emission nebulae: glowing plasmas
88 Reflection nebulae: celestial mirrors
90 Planetary nebulae: death shrouds
92 Supernova remnants: shattered star stuff

94 Galaxies... and beyond
96 Spirals: whirlpools in space
98 Barred spiral galaxies: the dominant spirals
100 Ellipticals: galactic fossils
102 Lenticulars: lens-shaped galaxies
104 Irregular galaxies: galactic black sheep
106 Radio galaxies: cosmic gushers
108 Quasars: at the edge of the Universe
110 Galaxy clusters: living in groups
112 Large-scale structure: superclusters and voids



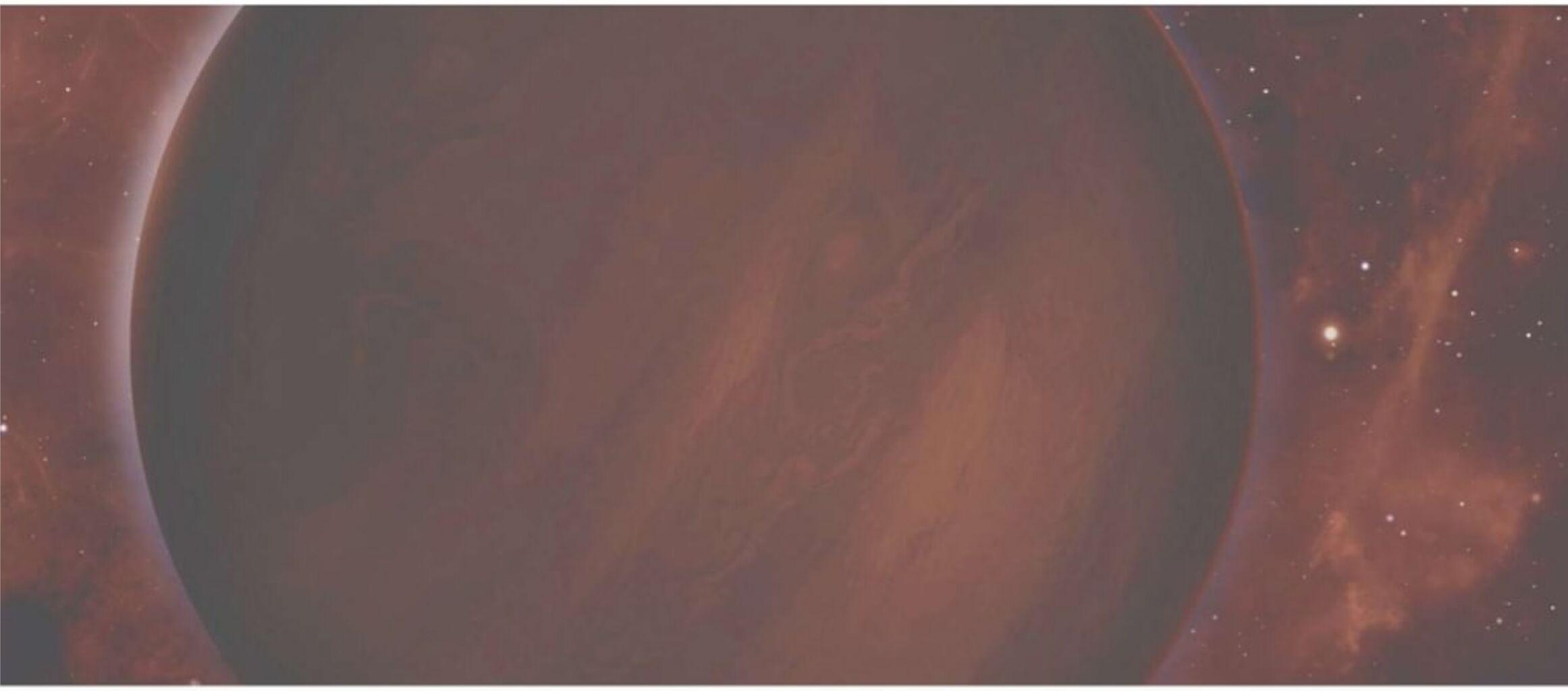
PLANETS
AND RELATED SPECIMENS

MOST PEOPLE have at least some idea of what a planet is. After all, we live on one: Earth. And if you have ever glanced up at the sky on a clear night, the chances are you will have seen other planets without necessarily knowing it. Venus and Jupiter are particularly dazzling, but to the untrained, unaided eye, they can easily be mistaken for bright stars. Up close, though, planets and stars are totally different objects. Stars (such as the Sun) shine by their own light. But planets emit no light whatsoever and give off very little heat. We're only able to see them by the light they reflect from the Sun.

Planets vary enormously from one specimen to another. By virtue of it being our home, we are all familiar with Earth: solid, rocky and generally clement. But it is nothing like the largest planets, the gas giants Jupiter and Saturn. Not only are these a good 10 times larger, they are entirely fluid, with no surface. You could never walk on Saturn – although a descent through its upper atmosphere would afford beautiful views of the planet's enigmatic rings. Then there are worlds like Mercury: rocky and metallic like Earth, but only one-third its size.

Related to planets are the dwarf planets. These are a relatively new category of object in the Solar System. Put simply, they are bodies that orbit the Sun, but which astronomers deem too small to be 'proper' planets. One of them, Ceres, is also categorised as an asteroid – another class of Solar System object, first discovered in 1801. Asteroids number in the tens of millions. While some are hundreds of kilometres across, like Ceres, the overwhelming majority are puny, potato-shaped lumps of rock, metal and carbon, orbiting the Sun between Mars and Jupiter.

There is more to the Solar System than just planets and asteroids, however: comets, for example – great 'dirty snowballs' that orbit the Sun; or planetary satellites, like the Moon; and then there are the trans-Neptunian objects that lurk in the outer reaches of the system. All of these objects are covered in this section. But first, we need to know where all this stuff came from, and when? ▷



Some 4,550 million years ago, the Solar System looked something like this. The Sun was still in formation, surrounded by a vast, warm disc – seen almost edge-on in this illustration – of dust, rubble and colliding worldlets. It is called the Solar Nebula

PLANETARY FORMATION

From gas and dust to planets, moons and a Sun. Where did all this stuff come from, and when?

THE AGE of the dinosaurs ended 65 million years ago. That's a time already far beyond human experience, but Earth, the Sun and everything in the Solar System is 70 times older still. At 4,550 million years of age, the Solar System is unimaginably ancient. Before that time, there was no Sun and no planets. There were only raw materials, in the form of a vast nebula of gas and dust called a giant molecular cloud (see page 80). This molecular cloud was knotty, with some regions being denser than others. In these denser regions, gravity pulled inwards and the knots got tighter still. And after a couple of million years, so-called globules developed, roughly spherical shells of gas and dust with a dense central core. Nearly five billion years ago, inside a cocoon much like this, the Sun and the planets were forged.

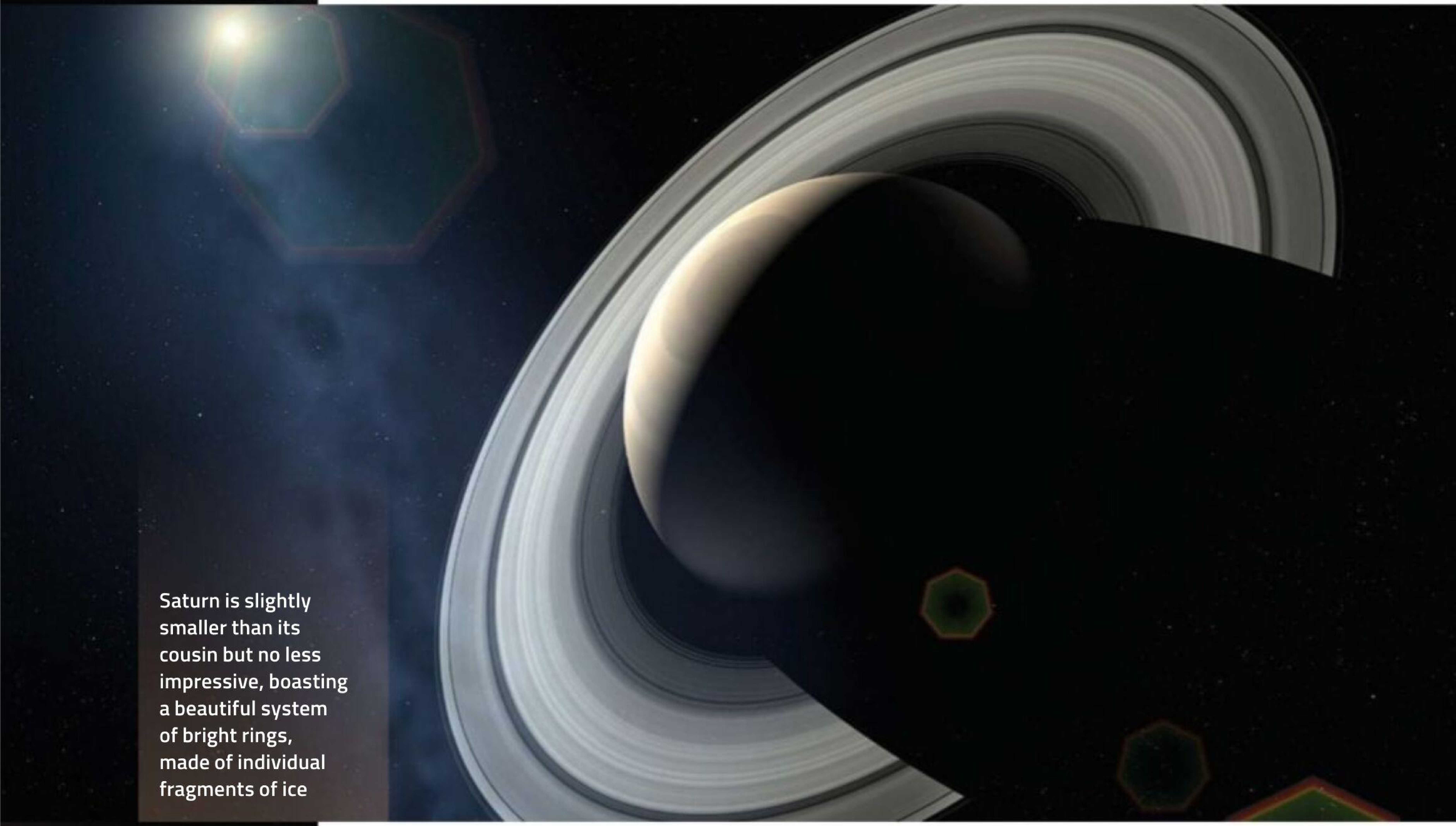
Gradually the solar globule contracted further under gravity, warming up as it did so. As it shrank, it began to spin faster and faster, like an ice skater pulling in her arms; and as it wound up, it flattened out. After 100,000 more years, the globule was transformed. In its place was a swirling, dusty pancake called the Solar Nebula – and in its hot central region, a glowing mass, bigger than the present orbit of Mercury, called a protostar (see page 28).

Millions of years later, with continued contraction and warming, the protostar eventually formed the Sun. Meanwhile, out in the disc, tiny particles of dust began to stick together, attracted by electrostatic forces. They grew bigger and bigger, into objects the size of pebbles, then rocks, then boulders. Still the collisions continued, until the boulders had grown into mountain-sized planetary building blocks called planetesimals. Once they had reached these dimensions, the impact rate shifted up a gear as the objects collided no longer by chance, but because of their mutual gravitational attractions. After a few more million years, most of the planetesimals had vanished, swept up into eight major planets, and countless millions of asteroids – debris from the formation of the Solar System that survives to this day. ▷

MARK GARLICK

Jupiter is the quintessential gas giant planet. It has no solid surface, just a vast, colourful envelope of super-compressed hydrogen and helium with, at its centre, a solid core of rock and ice about the size of Earth. One of its moons, Io, is seen transiting across its face

Scan to see an animation of Saturn and its moons



Saturn is slightly smaller than its cousin but no less impressive, boasting a beautiful system of bright rings, made of individual fragments of ice

GAS GIANTS

Massive, swirling and inhospitable: the hydrogen and helium worlds of Jupiter and Saturn

IN THE Solar Nebula, billions of years ago, there was a very strong temperature gradient. Close to the newly forming Sun, where it was hottest, icy substances were unable to condense – to turn from a gas into a liquid or solid – while substances such as iron and rock were readily able to do so. At a certain distance from the Sun, however, at the so-called snow line, the temperature dropped to a point where ices could condense. Icy particles are much more adhesive than the rocky and metallic ones that condensed closer to the Sun. And so, at the snow line, roughly five times further from the Sun than the present orbit of Earth, the planetesimals grew to planet-sized dimensions very quickly. In just 100,000 years or so, an icy kernel 15 times more massive than Earth appeared. This was destined to become Jupiter.

By far the most abundant elements in the Solar Nebula were the gases hydrogen and helium. They are very lightweight and fast moving, so are not easy for gravity to snare. But the icy, newly forming Jupiter had grown so massive that its powerful gravity was able to attract and catch even these lightweight materials. And so, for several hundred thousand years, Jupiter gorged itself, growing ever larger as it vacuumed gases from its surrounding environment until none were left and its growth was finally halted. The end result was a massive ball of hydrogen and helium, 11 times larger than Earth, as we know it today, with a solid core of rock and ice. Astronomers call this a gas giant.

Twice as far from the Sun, another gas giant formed: Saturn. But being so much further out, where the density of raw materials was that much less, Saturn was not able to grow to the dimensions of its larger cousin. It is a true giant, nevertheless, being a respectable nine times larger than Earth.

Gas giants are the largest planets we know of. Jupiter and Saturn are the only two in our Solar System, but elsewhere in space, orbiting other stars, these planets are very common indeed. ▷

MARK GARLICK X 2

Scan to see an animation of Neptune and Triton

ICE GIANTS

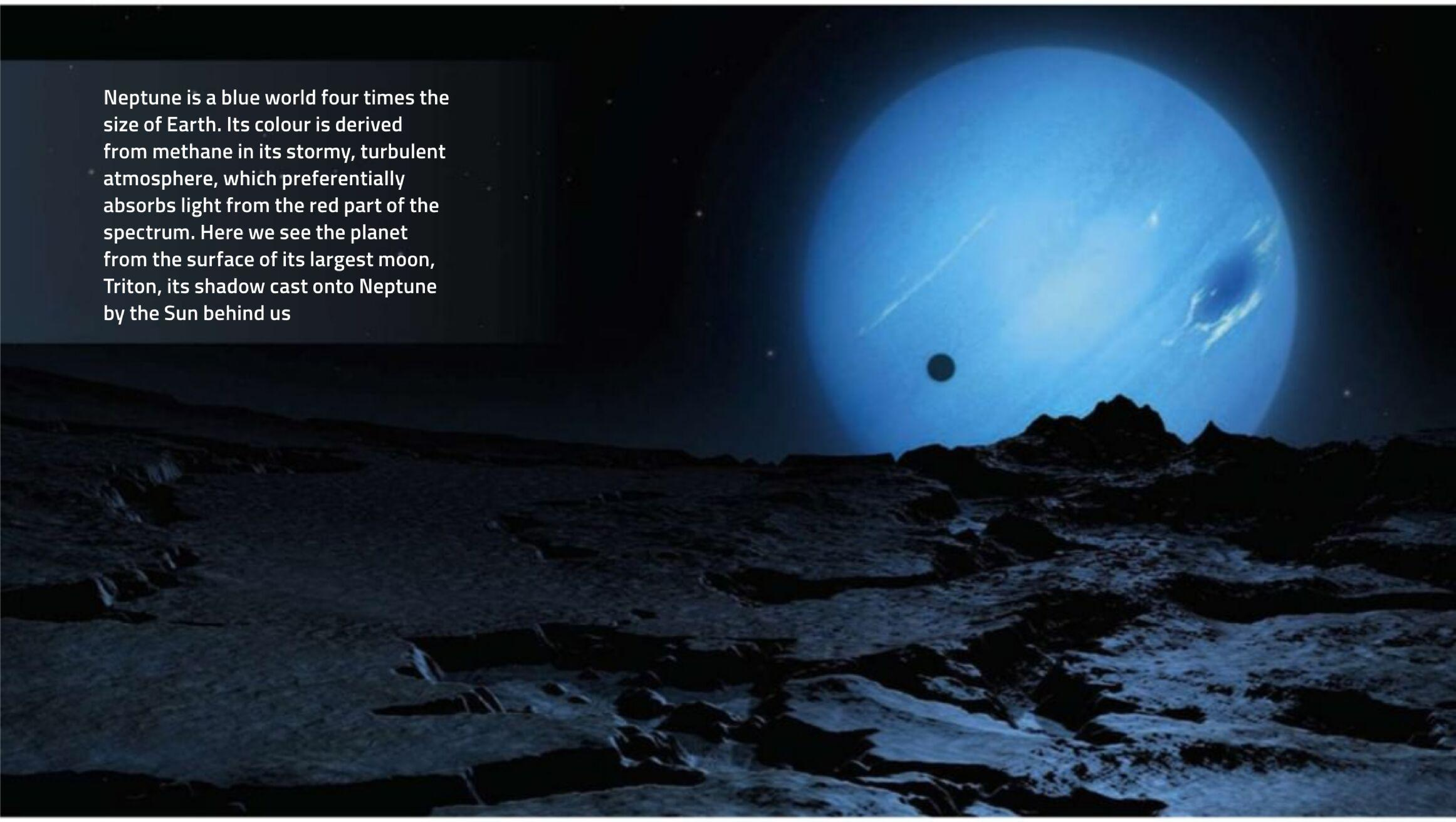
Neptune and Uranus: cold, blue worlds on the icy outer reaches

THE NEXT planets to appear were Uranus and Neptune, at still greater distances from the Sun than the gas giants. It's worth pausing for a moment to put these great expanses into perspective. Astronomers use a metric called the astronomical unit (or AU) to measure distances in the Solar System. One AU is the distance between the Sun and Earth, or 150 million kilometres. Today, Jupiter orbits the Sun at an average distance of 5.2 AU. (In fact, the orbit is not a circle but rather elliptical, as are the orbits of all the planets. But most planetary orbits are very nearly circular.) Saturn, by contrast, is found at 9.2 AU. Uranus is much further out, at 19.2 AU, and Neptune is right on the edge of the realm of the planets, fully 30 times further from the Sun than Earth.

At these great distances from the Sun, more than four billion years ago, the material in the Solar Nebula was spread extremely widely. Also, the time taken to orbit the Sun is much greater than the orbital period of Saturn, say. Both of these circumstances meant that Uranus and Neptune grew at a much slower pace than their giant siblings closer to the Sun. While Saturn and Jupiter had reached full size by about three million years after the appearance of the Solar Nebula, the growth of Uranus and Neptune took roughly three times longer – and they still ended up with only five per cent of the mass of mighty Jupiter.

Still, Uranus and Neptune are sizeable worlds. They are almost equal in size and mass, 17 and 15 times heavier than Earth respectively and four times its diameter. They lack the extensive hydrogen and helium mantles of the gas giants, however. While Jupiter is 90 per cent hydrogen, in Uranus and Neptune this gas makes up only about 20 per cent. In place of the hydrogen are ices of ammonia and methane. Thus, Uranus and Neptune are nowadays regarded as a separate class of planets: the ice giants. Worlds with similar make-ups have been found orbiting other stars. ▷

MARK GARLICK X 2


Neptune is a blue world four times the size of Earth. Its colour is derived from methane in its stormy, turbulent atmosphere, which preferentially absorbs light from the red part of the spectrum. Here we see the planet from the surface of its largest moon, Triton, its shadow cast onto Neptune by the Sun behind us

The other ice giant is Uranus, almost exactly the same size as Neptune. It is relatively featureless, lacking the clouds and storms of Neptune, but with a substantial ring system to compensate

TERRESTRIAL PLANETS

Earth and the three other rocky, solid worlds in our Solar System

THE FINAL planets to emerge from the chaos of the Solar Nebula were the smaller ones, of which Earth is the largest example. These are known as terrestrial or telluric planets – from the Latin words for Earth, tellus, terrestris or terra. The other terrestrial planets, three in all, are nothing like Earth. The term is used merely to describe planets with solid surfaces made of rocky and metallic materials.

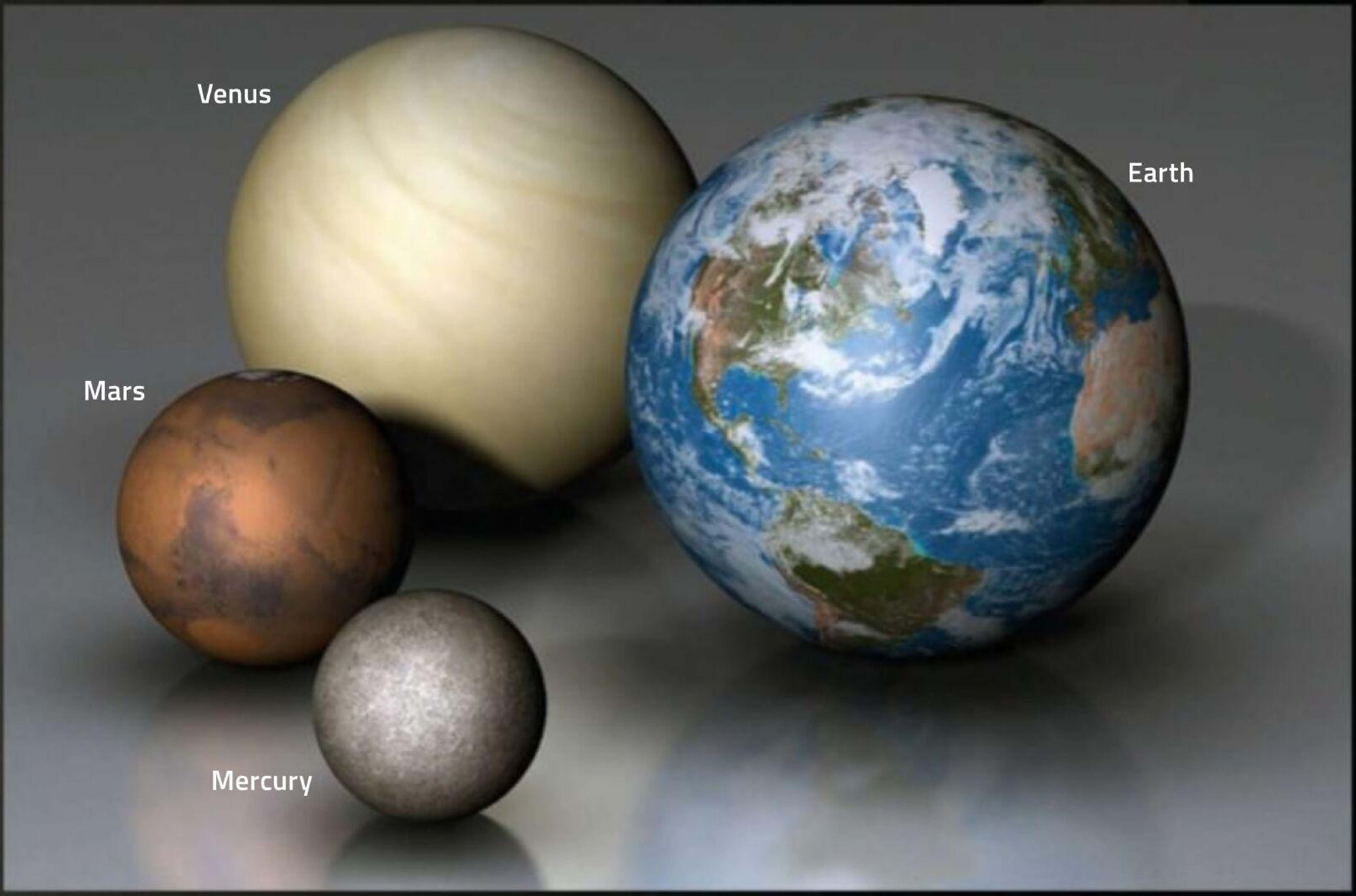
The growth of the terrestrial worlds – Mercury, Venus, Earth and Mars – was slow for a couple of reasons. First, the materials from which these worlds formed – rocks and metals – were much less abundant than the gases and ices that formed the outermost giant planets. Second, fragments of colliding rock or metal are much more likely to bounce off each other than chunks of ice, because the latter have much better adhesive properties. Thus, although the initial emergence of rocky and metallic planetesimals close to the Sun was fairly rapid, it took much, much longer for them to grow into fully fledged worlds.

After perhaps 10 million years, by which point the gas and ice giants had essentially stopped growing, four dominant protoplanets populated the inner Solar System, ordained to become the terrestrial worlds. But it took perhaps 10 times longer still for these worldlets to mop up the remaining planetesimal debris orbiting the Sun and grow to their full, modern sizes.

The terrestrial planets vary considerably in scale. Earth is the largest and most massive, while Venus is almost exactly the same size. Around other stars, so-called super-Earths have been found, some of them several times the diameter of our planet. Mars, meanwhile, is only half the diameter of Earth and Mercury only one-third (and made almost entirely of solid iron).

Astronomers think that Mercury, which is also the closest planet to the Sun, was originally much larger, and may have lost much of its mass during a collision with a similarly sized world billions of years ago. This may explain its heavy metal content – its outer rocky mantle might have been blasted away in the impact. ▷

MARK GARLICK X 2



Comparison of the four Solar terrestrial planets to scale. Earth is the largest of the foursome, with Venus a close second place. Mars is only 53 per cent the diameter of Earth and Mercury – the smallest planet – is 38 per cent

Mars is the second smallest of the Solar terrestrial planets. Its surface is replete with craters, great chasms and gigantic volcanoes – the largest in the known Solar System. The planet's red colour comes from the presence of rust, or iron oxide, which totally blankets the dusty, Martian soil

Scan to see an animation of the surface of Venus

ASTEROIDS

Carbon-rich, stony or metallic, millions of bodies in between Mars and Jupiter tell the tale of a violent past

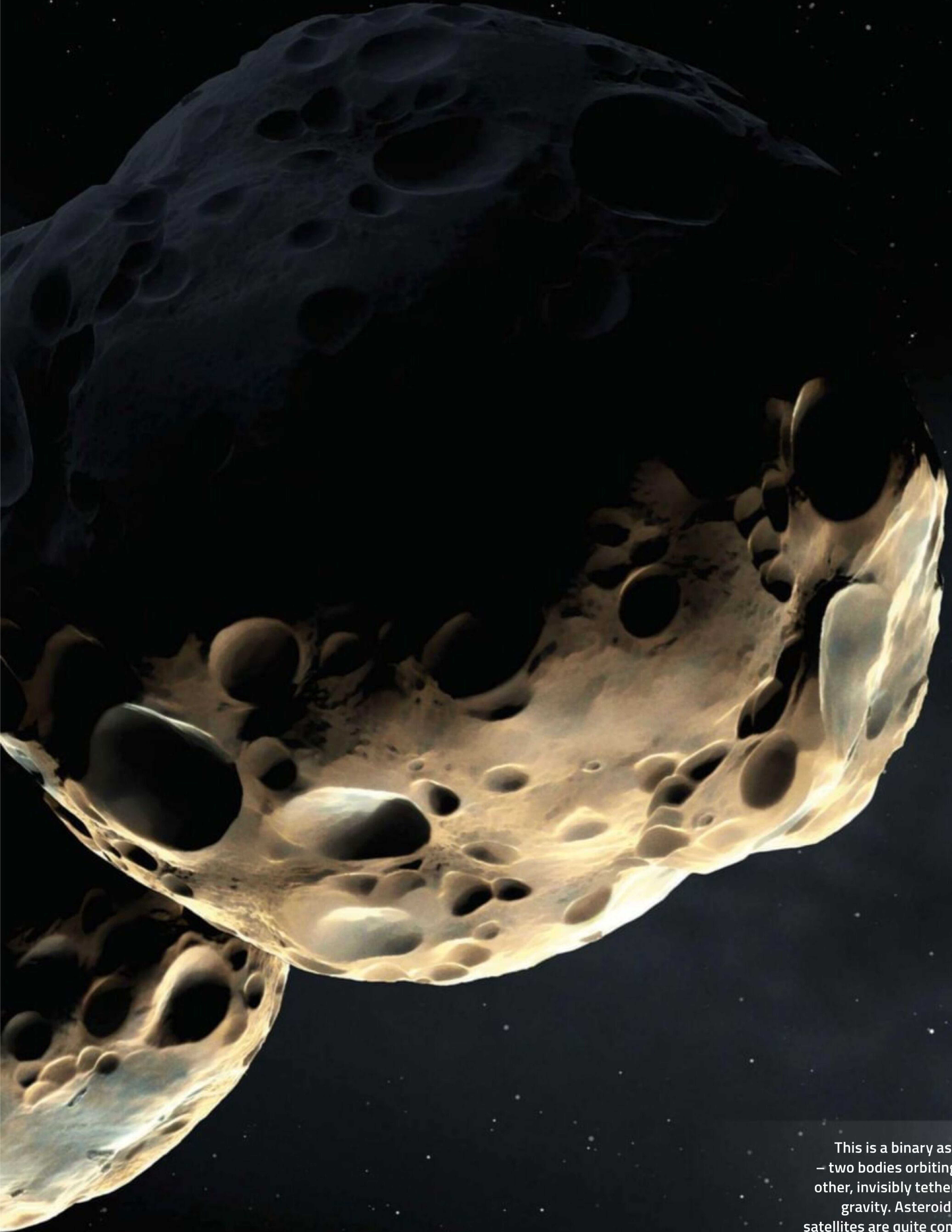
GIVEN HOW the Solar System was formed, it would perhaps be surprising if there were no remaining debris from that stormy period. And indeed, nearly five billion years later, the Solar System is full of leftover chunks of rock, metal and other materials which attest to its fiery birth. These primordial fragments of the Solar Nebula are known as asteroids.

Asteroids have been known since 1801, when the first one, Ceres, was found orbiting the Sun between Mars and Jupiter. Since then, astronomers have found hundreds of thousands of them. Like Ceres, most asteroids orbit the Sun between Mars and Jupiter, forming a doughnut-shaped cosmic junk yard called the asteroid belt. Others do reside outside the main belt, however. Ceres is by far the largest, at around 950km across. This world – also a dwarf planet (see page 19) – is the only asteroid that is large enough for its gravity to pull it into a sphere. Only three other asteroids are larger than 500km and most are much smaller still. All of these are irregularly shaped, like giant potatoes. Astronomers estimate that there could be as many as 25 million asteroids larger than 100m in diameter, fewer than 0.5 per cent of which are larger than 1km.

Asteroids come in various classes, depending on composition, but in general they are either carbon-rich (the most common), stony or metallic. We know what they are made of because occasionally fragments of asteroids – chipped off during collisions – fall to Earth as meteorites and can be studied. Using sophisticated dating techniques based on radioactive decay, scientists have measured the ages of these samples to a very high precision, leaving no doubt that they are remnants from the formation of the Solar System, billions of years ago.

It might seem puzzling that the asteroids did not coalesce into a single planet. The reason is that when asteroids venture too close to mighty Jupiter, lurking on the outer edge of the asteroid belt, they experience a gravitational tug and then develop wildly elliptical orbits. Some of them are flung out of the Solar System altogether, and others plunge into the Sun. This constant gravitational bullying ensures that the asteroids will remain, probably forever, individuals – a fossilised relic of the original Solar Nebula. ▷

MARK GARLICK



This is a binary asteroid – two bodies orbiting each other, invisibly tethered by gravity. Asteroids with satellites are quite common, although usually one component is much larger than the other

The view from the surface of the most celebrated and largest known dwarf planet, the icy Pluto. Its largest satellite, Charon, hovers motionlessly in the sky, cycling endlessly though its phases just like our own Moon

MARK GARLICK

DWARF PLANETS

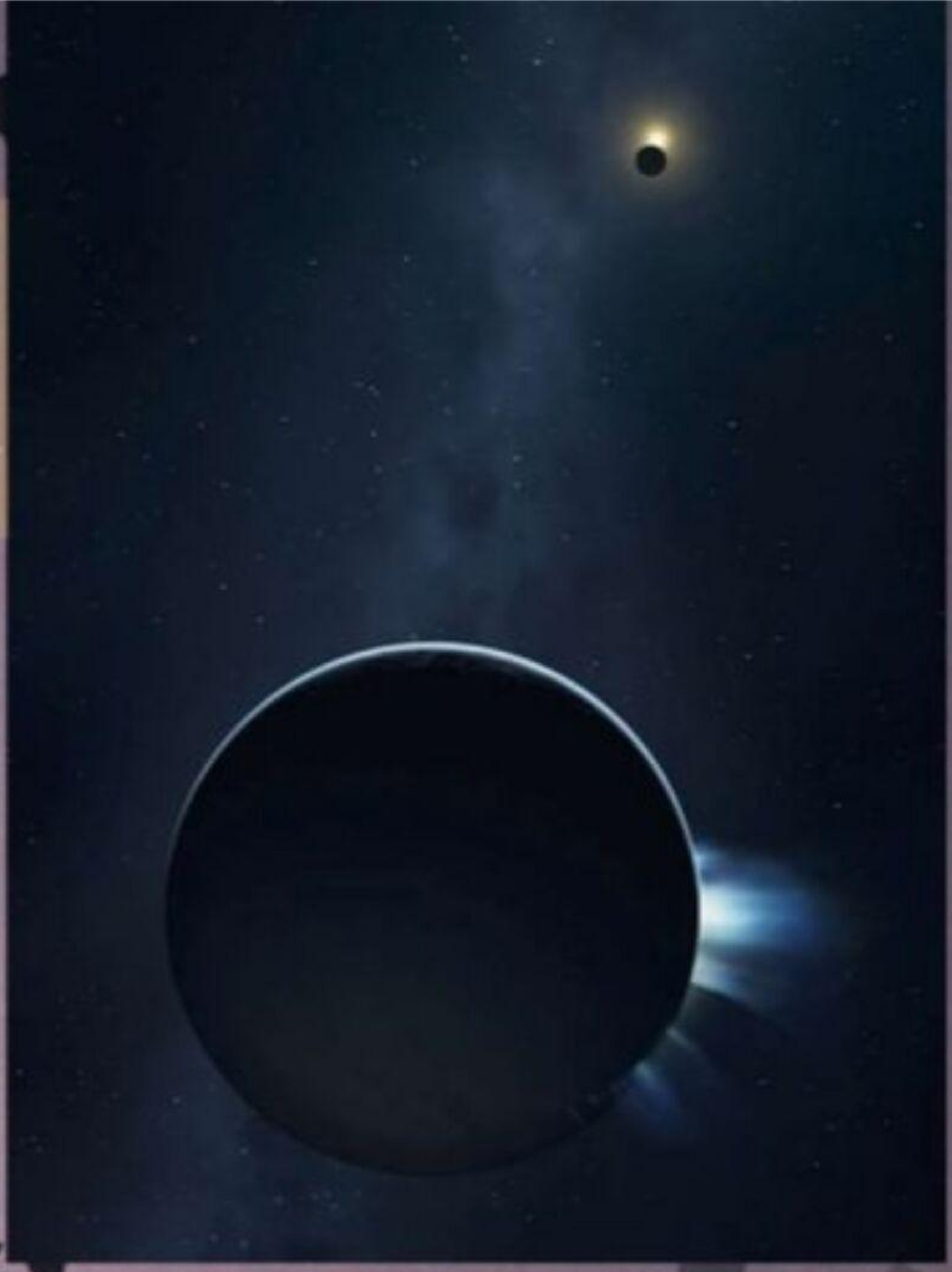
Pluto and our other enigmatic mini worlds

THE DWARF planets are a recent addition to the Solar System's interplanetary zoo, owing their definition to a world called Pluto. Pluto had been designated a planet since its discovery in the 1930s. But there was a problem. Researchers were discovering a growing number of mysterious bodies on the outskirts of the Solar System – trans-Neptunian objects. Some of these were almost the size of Pluto. One, Eris, was even suspected to be larger than Pluto itself (this has proven not to be the case). Surely these could not all be planets? What, in fact, is a planet? Up until 2006 there had been no formal definition.

That changed when a group of astronomers met to decide upon an official description of a planet. A planet, they concluded – though the definition is still subject to controversy among many astronomers – is an object that orbits the Sun; is massive enough that its gravity makes it spherical; and whose orbit is clear of other objects. Thus, the largest known asteroid, for example, Ceres, does not meet this definition, despite its round shape. Its orbit is shared with countless other worldlets in the asteroid belt. Similarly, the likes of Pluto and Eris share their orbits beyond Neptune with thousands of other icy worlds larger than 100km and trillions smaller still. Now Pluto, Eris and Ceres are known as dwarf planets. Two others, Haumea and Makemake, bring the present official dwarf planet total to five. Six others await confirmation.

Little is known about these enigmatic worlds, owing to their vast distances, some orbit out to 70 astronomical units. But all of them, except possibly Ceres, are largely composed of ices. Astronomers suspect that around 100 of the known trans-Neptunian objects are also dwarf planets, but their great distances and relatively puny sizes make it very difficult to accurately measure their shape. Even the largest dwarf planet, Pluto, is only around 2,376km in diameter. Earth is more than five times bigger and 458 times more massive. Like asteroids, the trans-Neptunian objects are probably the remains of the earliest stages in the formation of the Solar System. ▷

Scan to see an animated flight over Pluto



Enceladus is an icy moon of Saturn with a neat party trick: ice geysers. It can spew fountains of icy chemicals, including propane, ethane and acetylene, 500km into space

SATELLITES & RINGS

Orbiting companions: the moons and fragments circling almost every planet

SO FAR, everything we have looked at in the Solar System revolves around the Sun. But the Moon orbits Earth. It is our planet's only natural satellite. And Earth is not uniquely endowed. Most other planets have moons as well.

Indeed, Jupiter is like a miniature Solar System, boasting at least 79 satellites. Four of them – Io, Ganymede, Callisto and Europa – are substantial in size and spherical. They are called the Galilean moons, after their discoverer, Italian Renaissance astronomer Galileo Galilei. Each is a unique world, as rich in geology as any planet, and they are probably primordial. That is, they formed around Jupiter – in a dusty disc like the Solar Nebula but on a much smaller scale – while the planet itself was growing. The other moons of Jupiter are all much smaller, probably asteroids ensnared by Jupiter's mighty gravity. Saturn and Uranus are also surrounded by small armies of satellites. Again, some are large and spherical, and formed around the planets, while others are small and irregular gravitational captives. Neptune is the only giant planet that has no primordial moons, only captured ones. It is possible that Neptune had primordial moons long ago, but lost them due to collisions.

Of the terrestrial planets, only Earth and Mars have satellites. Mars's two are again irregular, just odd-shaped lumps of rock probably netted from the nearby asteroid belt. The Moon, Earth's large satellite, is a special case. It probably formed when a protoplanet crashed into the newly formed Earth and created a ring of debris around the young planet, which later coalesced. Many asteroids and dwarf planets have satellites also. They are the norm rather than the exception.

And finally, all of the giant planets have rings, the most famous being Saturn's. The rings are composed of immeasurable numbers of individual fragments, each like a mini satellite. These particles are so numerous that seen from afar the rings appear solid. Saturn's ring particles are made of ice, varying in size from a few metres down to microscopic. Uranus's rings are made of much darker, carbon-rich particles in the range 0.2 to 20 metres across. And the ring particles of Neptune and Jupiter are all probably microscopic. ▷

MARK GARLICK X 2

If a probe could enter the rings of Saturn and avoid an untimely destruction, this is the scene it might record. Countless icy boulders encircle the gas giant, slaves to its powerful gravity. Most are small, but some are as large as a house

Scan to see an animation of this image

Up close, a comet resembles an icy asteroid a few kilometres across, spewing geysers of ice from its surface as the Sun heats it up

Scan to see an animation of the Philae Lander on the surface of the Comet 67P/Churyomov–Gerasimenko

COMETS & COMET CLOUDS

'Dirty snowballs' spewing long, dusty tails as they near the Sun

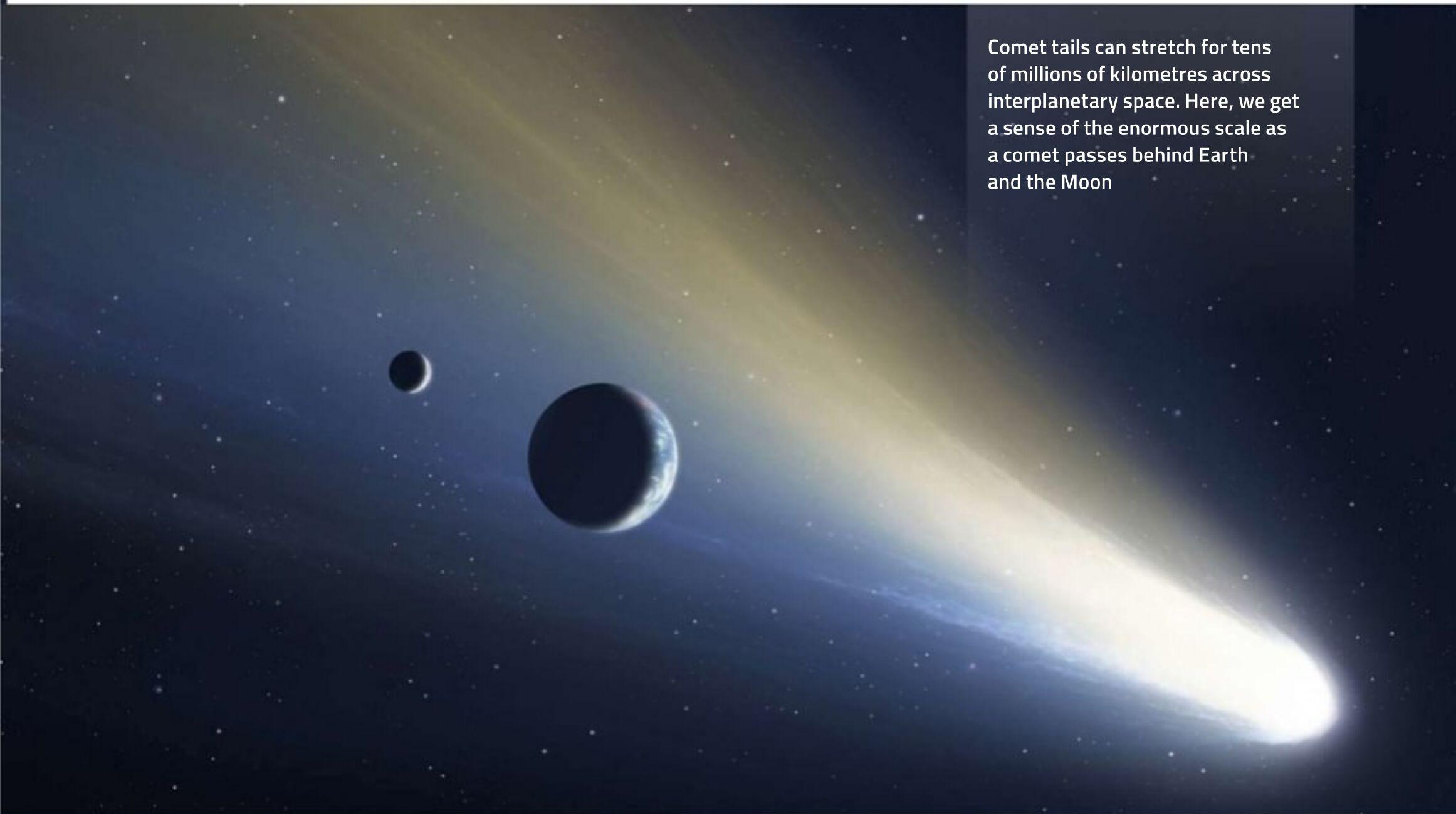
THE LAST class of objects in the Sun's family is the comets. Perhaps the most famous one is Halley's Comet, named after Edmond Halley, the astronomer who first correctly calculated its orbit. He examined historical comet sightings and realised that what was thought to be several comets was in fact a single object returning every 76 years. Comets, he proved, like planets, are objects that orbit the Sun with strict periodicity.

Like asteroids, comets are relics of the Solar Nebula, but their compositions are different. Asteroids formed close to the Sun, so are stony or metallic. Comets were fashioned much further out, where ices dominated. Probes have shown comets to be 'dirty snowballs', loosely packed chunks of ice, mixed with grit and riddled with voids, filled with gasses. They measure a few hundred metres to a few tens of kilometres across, much smaller than the largest asteroids.

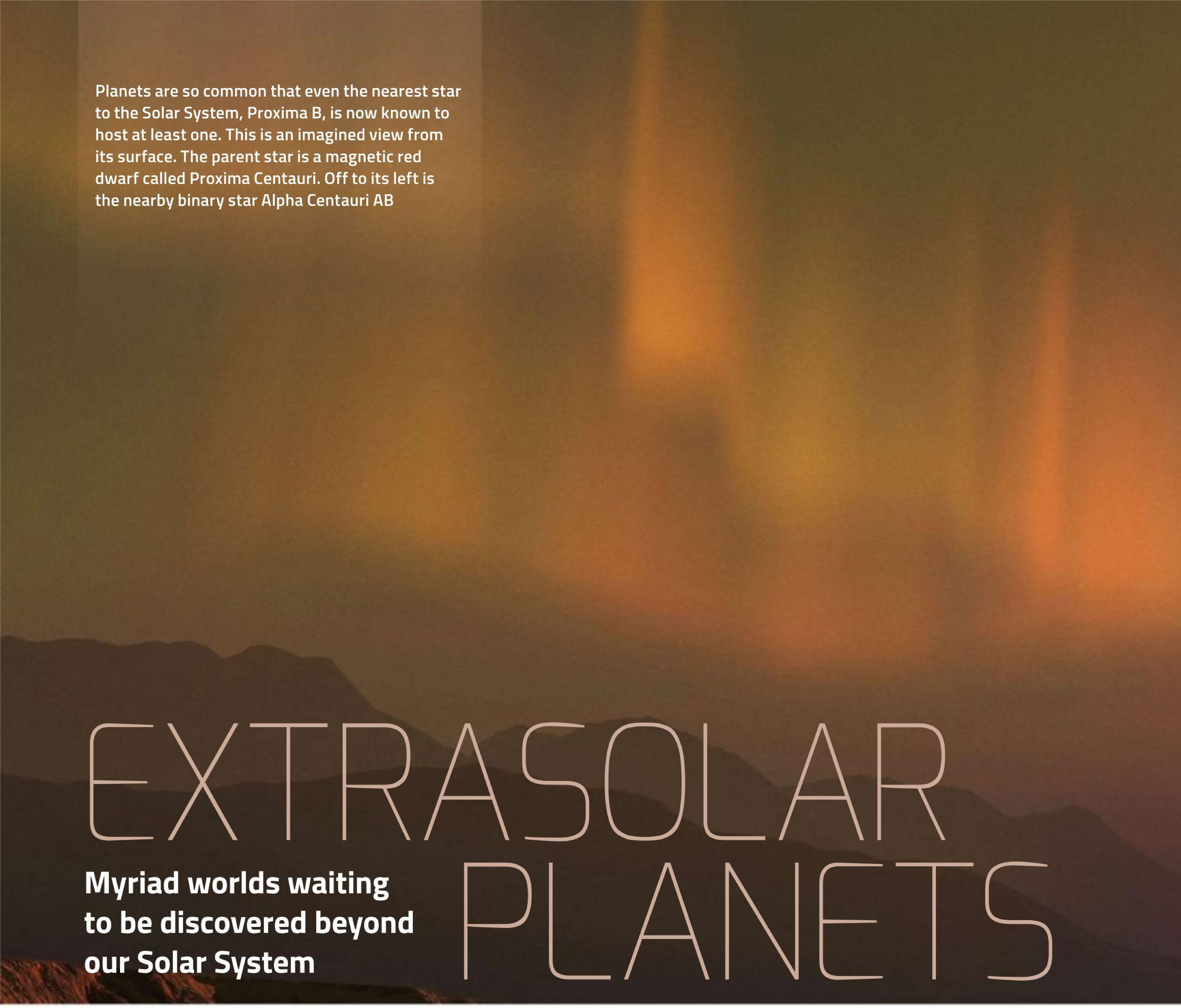
Comet orbits are very elongated. When far from the Sun, comets are dark, inert, difficult to spot. But as a comet nears the Sun, its surface ices start to boil and they stream off into space, surrounding the comet in a giant cloud called a coma. Even closer to the Sun, the Sun's own light and heat plays a part. Light is made of particles called photons, and in sufficient quantities it can exert a significant pressure. And tiny particles streaming out from the Sun (the solar wind) create an additional force. These forces push the coma away from the comet and deep into space to form a long, glowing tail pointing away from the Sun – the hallmark of a comet. In some cases, tails can stretch for tens of millions of kilometres.

Some comets, such as Halley's, have short periods, orbiting the Sun every few dozen years or so. Others can take thousands of years, spending much of that time at great distances from the hub of the Solar System. Astronomers think that long-period comets hail from a vast, spherical reservoir that surrounds the Solar System, perhaps 100,000 astronomical units across – that's 100,000 times the distance between the Sun and Earth. This is known as the Oort cloud. If it exists, as seems likely, the Oort cloud could be home to perhaps trillions of inert comets. ▷

MARK GARLICK X 2



Comet tails can stretch for tens of millions of kilometres across interplanetary space. Here, we get a sense of the enormous scale as a comet passes behind Earth and the Moon



Planets are so common that even the nearest star to the Solar System, Proxima B, is now known to host at least one. This is an imagined view from its surface. The parent star is a magnetic red dwarf called Proxima Centauri. Off to its left is the nearby binary star Alpha Centauri AB

MARK GARLICK

EXTRASOLAR PLANETS

Myriad worlds waiting to be discovered beyond our Solar System

THE SOLAR System is a dynamic, complex environment, with far more to it than a handful of planets clinging to a yellow star. Yet that star, the Sun, is but one of hundreds of billions in our Galaxy alone. As we gaze at the celestial dome on a dark, clear night, it is only natural to wonder if, huddled around the fires of those countless other stars, strange new worlds might exist. The answer is yes – and in huge numbers.

Astronomers announced the first unequivocal finding of an 'extrasolar' planet (or exoplanet) in 1992, orbiting a dead star called a pulsar (see page 44). But it was a discovery in 1995 that really excited the scientific community, when researchers in Geneva identified a planet orbiting a Sun-like star called 51 Pegasi. Exoplanets are very hard to spot. Next to the light of their parent suns, they are like flecks of dust caught in the glare of a floodlight. But 51 Pegasi's planet, now called Dimidium, was found indirectly. As the planet orbits, its gravity tugs on its star, which moves in sympathy in a small circle. From Earth, the star appears to wobble left and right. Astronomers can detect this motion and from it, infer the presence of the planet even though it is lost in the star's dazzle. Dimidium is the prototype of a new species of planet – the hot Jupiters. These are low-density gas giants in very tight orbits, so close to their parent stars that, as their name suggests, they are much hotter than Jupiter. Some are hotter than the coolest stars.

Since Dimidium's discovery, the number of known exoplanets has increased dramatically – almost 4,000 have been catalogued to date. When this planetary gold rush began, virtually all of the planets found were gas giants, including Dimidium. But instruments have become much more sensitive, allowing the detection of ever smaller worlds, some even smaller than Earth. These planets betray themselves when they pass in front of – or transit – their parent stars and cause the light level to dip by minute fractions of one per cent. Astronomers can spot this tiny reduction in light and from it deduce the presence of new worlds. The Kepler Space Telescope used this transit method and vastly increased the number of known exoplanets. Meanwhile, the Transiting Exoplanet Survey Satellite, or TESS, launched in April 2018, is expected to find as many as 20,000 more.

This is a dynamic field in astronomy and an important one. We now know that planets are the norm rather than the exception. Our Solar System is not in isolation. In the Milky Way alone, there could be trillions of alien planets.

Scan to see an animated version of this illustration

THE STELLAR ZOO

MARK GARLICK

ON A clear night, away from bright city lights, the stars twinkle as we gaze to the heavens. If we could venture among them and look back towards the Solar System, the Sun would all but vanish, lost amid the thousands of pinpricks of light that surround it. For the Sun is also a star; and the stars are suns, seen from very far away.

Stars are shining spheres of super-compressed, very hot gas and like gas planets, they have no solid surface. Keen observers might notice that they have subtle tints. This is because stars come in a wide range of temperatures. The cooler ones appear red and have 'surface' temperatures of around 2,500°C. Orange or yellow stars, such as the Sun, are a little warmer. The hottest stars, with temperatures in excess of 30,000°C, are blue or white. Stars also exhibit a mind-boggling range of sizes. For example, the gargantuan stars known as red supergiants (see page 40) measure hundreds of times the diameter of the Sun. At the other end of the scale are the tiny stellar corpses known as neutron stars (see page 44), which are no larger than a city. To put all this in perspective, the largest known red supergiants are as large compared to neutron stars as the Burj Khalifa skyscraper is to a bacterium.

Astronomers make sense of all this by categorising stars according to their colour, temperature and state of evolution. Stars develop constantly, within lifetimes varying from millions to trillions of years. This evolution is a result of nuclear reactions deep within a star's core. In the Sun, for example, a nuclear furnace converts a staggering two trillion tonnes of hydrogen into helium every hour. That's the mass of a small mountain consumed every second – for billions of years. This releases energy and an outward pressure that stops the Sun from collapsing under its own weight. In time, the hydrogen supply will begin to run dry and the Sun will change dramatically as it prepares for death.

In this chapter, we will learn how stars evolve – how they are born, how they age and how they die. Only then will it become clear why the range of sizes, colours and temperatures that typify the members of the stellar zoo is so diverse. ▷

Scan to see an animation comparing the Sun with the planets and largest known stars

PROTOSTARS:

YOUNG STELLAR OBJECTS

Vast molecular clouds collapse and contract under gravity… and a star is born

EVERYTHING HAS a prelude – even stars. They are born from vast patches of interstellar fog, lightyears across, known as giant molecular clouds (see pages 9 and 80). To recap, these nebulae are very patchy, with some regions that are denser than others. A denser neighbourhood, by virtue of its higher gravity, pulls in material from its surroundings and grows denser still. This increases its gravity even further, which, in turn, allows it to grow bigger and faster. At the same time, rotation within the growing cloud fragment causes it to flatten out.

The result, around a million years later, is a gigantic dusty shell called a globule. At the centre of this cocoon is a warming, gaseous clump about the size of the current orbit of Mercury, known as a protostar.

As its name suggests, a protostar is not yet a true star. While the latter is motorised by nuclear reactions, a protostar is powered only by gravitational contraction. To understand this process, picture a dam full of water. Contained, the water has gravitational potential – energy that it has by virtue of its influence under Earth's gravity. If the dam bursts, the water gushes out and its potential is unleashed as kinetic energy or heat, motion and sound. In the same way, a protostar is full of potential energy. As it falls in on itself under gravity, its potential energy decreases while its kinetic energy, in the form of heat, rises. The contracting protostar gets warmer and warmer.

The protostar stage does not last long. After about 100,000 years, the object becomes warm enough that the heat it generates starts to erode its birth cocoon. Gradually, it unveils itself to the Universe as a huge luminous mass, glowing like a dull red ember. The gravitational contraction continues until, around a million years later, the protostar's core temperature nears five million degrees Celsius. As this prelude to the stellar object's life as a true star draws to a close, it is set to enter a period of turmoil. ▷

MARK GARLICK

If we could peer inside the dark cocoon that surrounds a typical protostar, we might see something like this. The protostar, glowing red, may be flattened out by rapid rotation. It is still surrounded by a vast disc of gas and dust, around which planets will one day form

T TAURI STARS:
STELLAR ADOLESCENTS

The wind-whipped, electrically charged and unstable life of youthful stars

THE T TAURI phase in a star's development is extremely violent. The young star is still undergoing gravitational contraction, but it is not yet hot enough to drive thermonuclear reactions. However, with sufficiently hot surface temperatures around 4,000°C, virtually all its gases are electrically charged. In a normal gas, atoms are electrically neutral because they are made up of equal quantities of positive and negative charges bolted together. But if the gas is hot enough, the heat shakes the atoms apart. This process is known as ionisation and the charged atomic fragments are called ions.

So, a T Tauri star, like a true star, is a gigantic ball of electrically charged gas – a plasma. Compared to a star like the Sun, the average T Tauri is typically a few times larger and spins more quickly on its axis – once in a few days (the Sun takes a month). Since a moving charge constitutes an electric current, the star's interior is full of electricity. Just as a wire carrying an electric current generates its own magnetic field, the circulating ions inside a star create a global magnetic field. In the case of a T Tauri star, the rapid rotation creates a much stronger magnetic field than in most more normal stars. Furthermore, a T Tauri star is usually surrounded by the protoplanetary disc that built up around it as it grew. As the star rotates, its magnetic field lines are dragged through this disc. Where the field and disc interact, streams of gas are sucked out of the disc and pulled along the field lines onto the star's surface. Where these packets of gas hit, the star responds with violent magnetic flares – a hallmark of the T Tauri phase of star formation.

A final characteristic of a T Tauri star is a powerful stellar wind – a stream of ions that blusters away from the star, deep into space. The Sun has a similar wind, but it is much slower and more rarefied than the one in its T Tauri adolescence. ▷

MARK GARLICK

A T-Tauri star is a glowing ball of seething energy, covered in continent-sized starspots where powerful magnetic fields lower the temperature and hinder the flow of gases and the transfer of heat. Streams of gas are sucked out of the surrounding disc and charged particles are beamed into space to form a so-called bipolar outflow

The Sun is a main-sequence star with a surface temperature of around 6,000°C. The spots are typical of stars such as the Sun, but these darker, cooler regions of slightly lower temperatures are much smaller than during the T Tauri phase

MARK GARLICK

MAIN SEQUENCE STARS:

NUCLEAR POWERHOUSES

Scan to see an animated version of this illustration

We have ignition, as hydrogen fuses into helium

THE LENGTH of a star's T Tauri phase varies enormously, depending on the star's mass. For a star like the Sun, for example, this troubled period of stellar adolescence lasts about 30 million years. But in all cases there is a common event – one that ends the T Tauri stage, stops the star's gravitational contraction and puts it squarely on what astronomers call the main sequence. That event is the ignition of thermonuclear reactions in the star's core. It occurs once the internal thermometer clocks up around 10-15 million degrees Celsius.

At these extreme temperatures, the positive hydrogen ions deep within the star's core are moving so quickly that when they hit, they overcome their mutual electrostatic repulsion and stick together. A series of chain reactions is set up and the hydrogen ions are consumed slowly, converted into a new element: helium. This process, known as stellar nucleosynthesis, releases an enormous amount of energy and a corresponding outward pressure. For the first time in the star's existence, the inexorable inward pull of gravity, which has continuously shrunk the star until now, is halted, exactly balanced by the core's new-found outward pressure. Astronomers call this situation hydrostatic equilibrium and it is the very definition of the main-sequence phase.

The main sequence is the longest period in a star's lifetime. The Sun has burned hydrogen like this for 4,600 million years and it is still not halfway to its end. But, as with the T Tauri period, the duration of the main sequence depends critically on the star's mass. In a much more massive star, the core has so much weight pushing on it that it consumes its hydrogen supply far more quickly to generate enough outward force to counteract gravity. Such stars tear through their hydrogen stockpiles in only a few million years. But very low-mass stars, staggeringly, live a million times longer. They are known as red dwarfs. ▷

Red dwarfs are the most common stars in the known cosmos. Of the 63 stars within 16 lightyears of the Sun, 50 are red dwarfs. This image shows a typical example, feeble and dim, seen from the vicinity of an imagined orbiting world

RED DWARFS:

FEEBLE AND FAINT

The most common stars are faint, slow-burning and long-lasting

MAIN-SEQUENCE stars are known as dwarfs, which does not mean they are small – it's just that more evolved stars tend to be bigger. Red dwarf stars, however, are deserving of the term, having only a fraction of the Sun's mass, diameter and luminosity. So dim are they that not one is visible to the naked eye – even the nearest, Proxima Centauri, only 4.24 lightyears away, is 100 times too faint to spot.

Red dwarfs have such a puny mass that the pressure at their centres – from the weight of the rest of the star – is relatively low. These stars, therefore, do not need to generate much energy to prevent gravitational collapse, so they consume their hydrogen stockpiles sedately. In addition, red dwarf interiors are fully or mostly convective, like pans of boiling water. The heat generated in the core rises to the surface where it spreads out, cools and sinks down to be reheated. Consequently, red dwarfs are like huge convection heaters, with thoroughly churned and mixed interior gases.

In a Sun-like star, by contrast, the gases higher up do not mingle with those in the core. Once the Sun exhausts its core hydrogen, the rest of the hydrogen higher up is largely untouched, like a campfire that burns in the middle and leaves the edges unscathed. Inside a red dwarf, even hydrogen on the surface is transported to the core, where it is consumed during the main sequence. This combination of a slow fusion rate and a large hydrogen supply means that a star like Proxima is expected to be on the main sequence for an astonishing four trillion years – 290 times the current age of the Universe!

Still, not even the stars are eternal. Once the hydrogen supply begins to run dry, replaced slowly and inexorably by a helium 'ash', the stage is set for the next phase in a star's evolution. Leaving the main sequence behind, it becomes a subgiant. ▷

MARK GARLICK

SUBGIANTS: GROWING OLD

The aging star begins consuming the hydrogen outside its shrunken core

ONCE A star begins to run out of the hydrogen gas it needs to generate its life-sustaining nuclear reactions, it is on dangerous turf. Its long period of stability on the main sequence ends – and death is near. The problem is helium – the product of a star's hydrogen reactions. Helium ions carry four times the electric charge of their simpler hydrogen counterparts. In order to fuse helium ions in a nuclear reaction, they have to move much quicker than hydrogen ions to overcome their mutual electrostatic repulsions and bond. In other words, much higher temperatures are needed to fuse helium than to fuse hydrogen. So when the hydrogen runs dry, the nuclear reactions in the star's centre turn off and gravity takes over. The star's core, lacking its internal pressure source, starts to shrink.

This renewed contraction brings only a brief respite, however. While the star was on the main sequence, it depleted the hydrogen in its core but not in those regions above it (unless the star is a red dwarf). The gravitational squeeze, therefore, brings this fresh, unused fuel into the core region, where it is hot enough to react. Once again, the star is stable, converting hydrogen into helium in a narrow shell on the outskirts of the dead, reactionless, helium core. As a result of this period of thermonuclear frenzy, the star's outer layers expand with the renewed energy pouring into them. While the core continues to shrink, the star as a whole grows gradually larger and cooler – becoming a subgiant.

Subgiants constantly evolve and expand, while their cores contract and heat up. For the Sun, this phase is expected to persist for 700 million years, swelling to three times its main-sequence diameter. Eventually, though, even the hydrogen shell is exhausted and this triggers another crisis. The star is then poised for its most dramatic metamorphosis to date. ▷

MARK GARLICK

There is little to tell a subgiant star apart from a younger one on the main sequence. Altair, for example – a white star in the constellation of Aquila – is thought to be a subgiant, but astronomers are not entirely sure

A blue giant star, powerful and ultra-luminous, ravages the surface of this nearby rocky world. These stars can pump out as much as 10,000 times the power of the Sun

GIANTS: GERIATRIC STARS

The bright, swollen fate awaiting our own Sun

SUBGIANTS MAY be dramatic, but they are puny compared to the stars that they are destined to become. A subgiant's core is contracting all the time, heating up as it does. Once the core temperature is high enough, so much energy is generated that the radiation pushes on the star's outer layers and puffs them up to even greater dimensions. With a typical diameter of a few dozen to hundreds of times larger than a normal main-sequence star, and 1,000 to 10,000 times brighter, these stars are known as red giants.

When the Sun reaches the end of its life, it will expand into a red giant, with an expected diameter of around 200 times its current size – easily large enough to engulf the innermost planets, possibly including Earth. Eventually, with its core constantly shrinking as it runs out of reactionable fuel, its internal temperature will reach a staggering 100 million degrees Celsius. That's the magic number needed to fuse helium ions together. Suddenly, nuclear reactions begin anew, this time feeding on the helium and creating a new ash – carbon and oxygen. The core, alive once again, will spew fresh energy outwards, puffing up the star's outer layers even more, until they start to escape from the star altogether, forming a planetary nebula (see page 91).

Generally, astronomers use 'giant' to describe stars that are much larger than main-sequence stars of the same temperature and hence colour. So, not all giant stars are red. Alcyone is a blue giant that has exhausted the hydrogen in its core and swollen beyond its main-sequence radius. It's on its way to becoming a red giant, as are most other non-red giant stars. For many stars, including the Sun, a red giant is the endpoint of stellar evolution. But for the most massive stars, heavier than about eight to ten Suns, the end is even more impressive. ▷

MARK GARLICK

SUPERGIANTS:
LUMINOUS POWERHOUSES

Red or blue, these bright behemoths give new meaning to the word 'big'

THE MOST massive stars, outweighing the Sun by factors of 10 or more, do not follow the same evolutionary trend – main sequence, subgiant, giant and red giant – as their smaller siblings. Rather, they evolve off the main sequence into exceptionally luminous powerhouses called blue supergiants. These monsters are unimaginably bright, some shining with the brilliance of at least 10,000 stars like the Sun – and in some cases, up to a million.

Despite this power and their great mass, blue supergiants are not as large as their name suggests. The biggest are around 25 times the diameter of the Sun. This is certainly huge, but red giants are an order of magnitude bigger still. The difficulty is that, in astronomy, terms such as 'giant' and 'supergiant' are used – somewhat counterintuitively – not to refer to the star's size but to its state of evolution. Younger stars (main sequence) are dwarfs; more evolved ones are subgiants; and the most evolved are giants. A very massive, bright main-sequence star might be bigger than a more evolved but less massive subgiant.

The largest stars, though, are the red hypergiants, which evolved from blue supergiants. Blue supergiants are so powerful that they constantly lose gas – they are literally blown apart by the pressure of their own intense radiation. This puffs them up to dimensions that give new meaning to the word 'huge'. While red giants – formed from relatively low-mass stars – may approach 200 solar diameters, the largest known red hypergiant, UV Scuti, is an astonishing 1,700 times the size of our Sun. If placed at the centre of the Solar System, it would engulf all the planets out to and including Jupiter, almost reaching the orbit of Saturn.

Some stars evolve from blue supergiants to red supergiants or hypergiants, then back to blue again. This happens because as the red star loses its outermost layers, the hotter, bluer and smaller interior is revealed. The star settles down again as a blue supergiant, before billowing up once more to its supersized red alter ego. ▷

MARK GARLICK

Red giants are not perfect spheres. Because they are convective, their envelopes are made up of bubbling cells of gas, rising to the surface and spreading out again before sinking. In this image, a luckless planet is destroyed as its star expands to truly monstrous proportions

The cold glare of a white dwarf spills over the battered landscape of a once verdant world. A fate such as this awaits Earth in the distant future – if it is not swallowed first when the Sun becomes a red giant

WHITE & BLACK DWARFS:

STELLAR CORPSES

Its fuel exhausted, an inert, super-dense core is all that remains

THE STARS we have met so far have been 'alive', in the sense that they hold their own against the crush of gravity by fusing elements together deep within. But when this nucleosynthesis ends, gravity finally wins. The star must face death. A low-mass star becomes a red giant and sheds its outer layers to form a planetary nebula (see page 91). Once this process is complete, all that is left of the once mighty star is its naked core – inert, yet still very hot: a white dwarf.

White dwarf stars are made of helium, or carbon and oxygen – the products of nucleosynthesis. They are exceedingly compact. Once a star leaves the main sequence, its existence is a constant battle as the core struggles to generate enough energy to balance gravity. For hundreds of millions of years (in the case of a solar-mass star), the core contracts. All its material will eventually be squeezed into a super-dense sphere with only one-millionth of the star's original volume. The result: a typical white dwarf is no larger than a terrestrial planet like Earth – though it may outweigh the planet by a factor of 200,000.

White dwarfs, therefore, have absurdly high densities. Just a teaspoon of their substance would weigh as much as a pickup truck. A material such as this is called a degenerate gas. Essentially, the electrons are crammed so close together that there is no space between them. So while white dwarfs are inert, they are stable. Not even gravity can squeeze the electrons closer together.

Because white dwarfs lack an internal energy source, they resemble planetary-sized lumps of coal. Gradually, they are destined to grow cooler and darker, until they emit no light at all. They are then called black dwarfs. Astronomers have a long time to wait before they will be able to detect any, however, because a black dwarf is expected to take, at the very least, a quadrillion years to form – far, far longer than the current age of the Universe. ▷

MARK GARLICK

A pulsar is a city-sized sphere of super-dense matter, emitting beams of electromagnetic radiation and spinning sometimes hundreds of times per second. If the pulses intercept the Earth, we observe a cosmic lighthouse as the radiation beams sweep across our line of sight

MARK GARLICK

NEUTRON STARS & PULSARS:

THE ULTIMATE DENSITY

The small, incredibly dense end for massive stars

WE HAVE seen what happens to a star of low to moderate mass when it dies. In the case of a somewhat heavier star, the final death throes are much more energetic, and the corpse is an object even stranger and denser than a white dwarf: a neutron star.

White dwarfs are balanced against collapse by electron degeneracy pressure. But for stellar cores more massive than about 1.4 solar masses, even this is not enough. The relentless gravitational crush causes the ions of helium, oxygen or carbon to shatter into their constituent subatomic particles, called protons and neutrons. The protons join with electrons – positively and negatively charged respectively – to make more neutrons. Suddenly, the core is full of neutrons and little else. This frees an enormous amount of space and allows the core to contract even further, stopping only when the neutrons reach degeneracy. Neutron stars are far denser than white dwarfs; as dense as the entire human population, more than seven billion people, squashed into the volume of a sugar cube. These stars are no larger than a small city, mere kilometres across.

Another astonishing quality of neutron stars is their rapid rate of spin. Just as an ice skater spins up when they pulls in their arms, a star spins quicker as it shrinks. Since a neutron star is around 50,000 times smaller than its main-sequence radius, the increase in rotation is phenomenal. These stars can spin on their axes hundreds of times every second. In addition, they have super-amplified magnetic fields, 10 billion times stronger than a fridge magnet. These fields cause the stars to emit beams of light and radio energy along their magnetic axes. If the Earth is in sight of these beams, we receive a pulse of radiation with each turn of the star, hundreds of times per second. These neutron stars are known as pulsars. ▷

This is a special type of black hole called a supermassive black hole. These are thought to lurk at the cores of many – perhaps most – galaxies, including the Milky Way. It is surrounded by a swirling pancake of gas, the remains of stars that ventured too close. The gases are heated to extreme temperatures and emit vast quantities of deadly X-rays, betraying the hole's presence

BLACK HOLES: LIGHT TRAPS

Infinitely dense, indefinitely collapsing stellar zombies

WHITE DWARFS and neutron stars are certainly awesome, but a stranger fate awaits the Universe's heaviest stars. White dwarfs are stable if they are less massive than about 1.4 solar masses. Any larger and gravity overwhelms the pressure of the degenerate gas and the ions shatter, forming a neutron star. Neutrons are crammed against each other; the star is essentially a city-sized subatomic particle. These stars withstand their own gravitation because there is no space between the neutrons – but only up to a point. In neutron stars weighing more than three solar masses, the neutrons splinter – then nothing known to science can stop the star collapsing indefinitely. It shrinks until it has zero size and infinite density. Only its incredible gravity remains. These exotic stellar zombies are called black holes.

On Earth, when you throw a ball up, gravity slows it down; it reverses direction and falls to the ground. If a ball is launched fast enough though (at a speed of about 11km/s), it can overcome gravity and escape into space. But a black hole's gravity is so powerful that no object will ever escape, however fast it's travelling. Even light, which travels at the Universe's ultimate speed limit, 300,000km/s, is held down. Black holes emit no electromagnetic radiation, including light, of any kind. This gives them their name. (Quantum mechanical effects come into play near black holes, meaning that they can 'leak' something called Hawking radiation – but that's another story.)

Astronomers have found many cases where an invisible object, a suspected black hole, orbits a normal star. The black hole's gravity warps its companion into an egg shape, pulling gas from its atmosphere. Just before they vanish into that gaping maw, the gases are so hot that they shine brilliantly in X-rays. Here gravitational potential energy is converted to heat as the gases flow inwards. Astronomers detect this and infer that a black hole must be there. They can measure its mass using the laws of motion and be confident it is a black hole if it is heavy enough. ▷

MARK GARLICK

BROWN DWARFS:

FAILED STARS

Too small to be stars, too large to be planets

THE FINAL type of stellar objects are not really stars, but they are not planets either. They occupy the middle ground between massive planets and flyweight stars. These are the brown dwarfs.

Stars are created when a gas cloud collapses under gravity, forming a central mass with a disc of gas and dust around it. Astronomers think that brown dwarfs are created in the same way, except they never accumulate enough mass to synthesise helium from hydrogen. The reactions to do this require a core temperature of at least 10 million degrees Celsius, but a typical brown dwarf's core never gets hotter than about half that and often it is a hundred times cooler still. For this reason, some people refer to brown dwarfs as failed stars. Nevertheless, their cores are hot enough that a special form (or isotope) of hydrogen, called deuterium, can undergo fusion reactions, leading to the synthesis of a helium isotope called helium-3. And the most massive brown dwarfs are able to produce ordinary helium by consuming another element, lithium. So, despite not making the grade as true stars, the heaviest brown dwarfs do still emit a substantial amount of light, courtesy of their nuclear cores, which can be comparable to that emanating from the faintest true stars.

Brown dwarfs vary in size, from around the diameter of Jupiter to a few times larger, which makes them much denser than a planet, as typically they weigh between 13 and 75 Jovian masses. They have surface temperatures ranging from the freezing point of water to around 2,500°C. To the naked eye, a brown dwarf appears deep red or magenta, depending on how hot it is, although those with low surface temperatures emit no detectable light and will only be visible to the eye if they orbit and are illuminated by an actual star. Intriguingly, some of these objects have weather patterns – planet-sized storms and swirling cloud bands, similar to those of Jupiter. Unlike Jupiter, though, clouds found in the atmospheres of brown dwarfs are made of hot grains of sand and iron. ▷

MARK GARLICK

A brown dwarf is a cosmic oddball – neither a planet nor a star, yet with traits of both. It might be enveloped in dark bands of cloud, obscuring the warmer, brighter layers below. In this image, a brown dwarf is orbiting a normal star (left)

CAMARADERIE OF THE STARS

LIKE LIVING organisms, stars favour companionship. The pinpoints of light that speckle the night sky are not all individuals; many of them are pairs or groupings of higher multiples. They are not simply chance groupings, either – two or more stars that merely appear close together. No, these are actual physical associations – stellar systems in which two or more members engage in a stately gravitational dance about their centre of mass. And sometimes this stately dance turns into something altogether more frenetic.

Astronomers estimate that between one quarter and one half of all the stars in the Milky Way are binary or multiple-star systems. If you examine the 20 stars nearest to the Sun, for example, you will find that there are not 20 stars at all – in fact, there are 31. Two of them are triple-star systems (including Alpha Centauri, the closest star system to the Sun) and seven of them are binary. Only the remaining 11 stars are truly single.

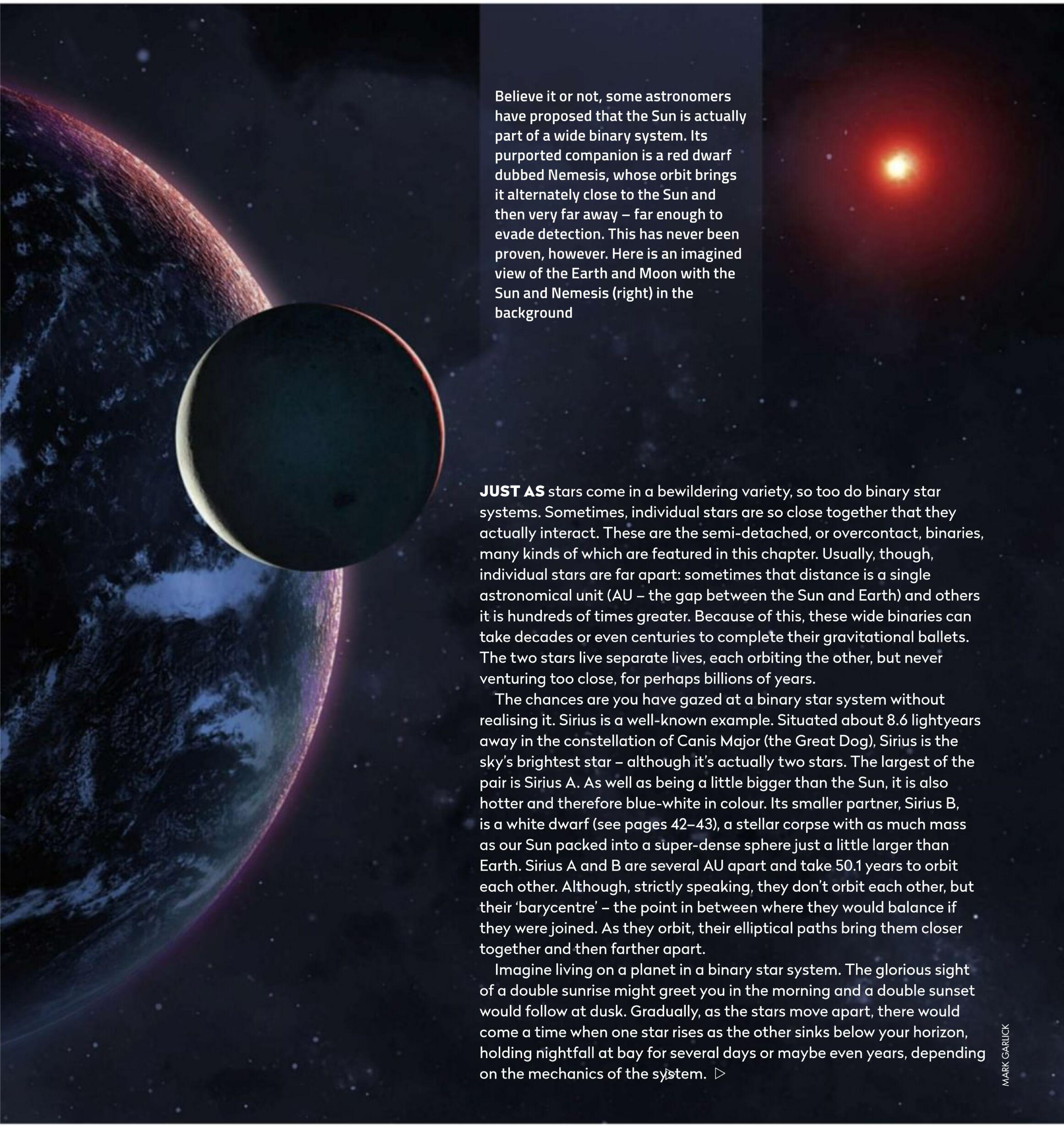
So how does this stellar camaraderie arise? Well, multiple-star systems are common because, in general, that is how stars are born. We know this from the sheer scale of interstellar space. Imagine you reduced the Sun down to the size of a pea, a scale reduction factor of about 140 billion. Yet, even with this degree of miniaturisation, you would still have to travel nearly three kilometres before you encountered the Sun's nearest neighbours.

Space is mostly empty. It is because of the sheer amount of nothingness in the Universe that we can be sure that multiple-star systems are, generally, not the result of stars just passing by each other. Although chance encounters happen, they are far too infrequent to account for the degree of binaries and multiples that we see. The only conclusion is that stellar multiplicity is a product of stellar formation. In this chapter, we will meet some of these gregarious stars and learn about stellar evolution along the way. ▷

MARK GARLICK

WIDE BINARIES

Stellar pairs bound together but far apart, separate but in sync



Believe it or not, some astronomers have proposed that the Sun is actually part of a wide binary system. Its purported companion is a red dwarf dubbed Nemesis, whose orbit brings it alternately close to the Sun and then very far away – far enough to evade detection. This has never been proven, however. Here is an imagined view of the Earth and Moon with the Sun and Nemesis (right) in the background

MARK GARLICK

JUST AS stars come in a bewildering variety, so too do binary star systems. Sometimes, individual stars are so close together that they actually interact. These are the semi-detached, or overcontact, binaries, many kinds of which are featured in this chapter. Usually, though, individual stars are far apart: sometimes that distance is a single astronomical unit (AU – the gap between the Sun and Earth) and others it is hundreds of times greater. Because of this, these wide binaries can take decades or even centuries to complete their gravitational ballets. The two stars live separate lives, each orbiting the other, but never venturing too close, for perhaps billions of years.

The chances are you have gazed at a binary star system without realising it. Sirius is a well-known example. Situated about 8.6 lightyears away in the constellation of Canis Major (the Great Dog), Sirius is the sky's brightest star – although it's actually two stars. The largest of the pair is Sirius A. As well as being a little bigger than the Sun, it is also hotter and therefore blue-white in colour. Its smaller partner, Sirius B, is a white dwarf (see pages 42–43), a stellar corpse with as much mass as our Sun packed into a super-dense sphere just a little larger than Earth. Sirius A and B are several AU apart and take 50.1 years to orbit each other. Although, strictly speaking, they don't orbit each other, but their 'barycentre' – the point in between where they would balance if they were joined. As they orbit, their elliptical paths bring them closer together and then farther apart.

Imagine living on a planet in a binary star system. The glorious sight of a double sunrise might greet you in the morning and a double sunset would follow at dusk. Gradually, as the stars move apart, there would come a time when one star rises as the other sinks below your horizon, holding nightfall at bay for several days or maybe even years, depending on the mechanics of the system. ▷

NOVAE

When companion stars get too close their partnership ends in an incandescant explosion

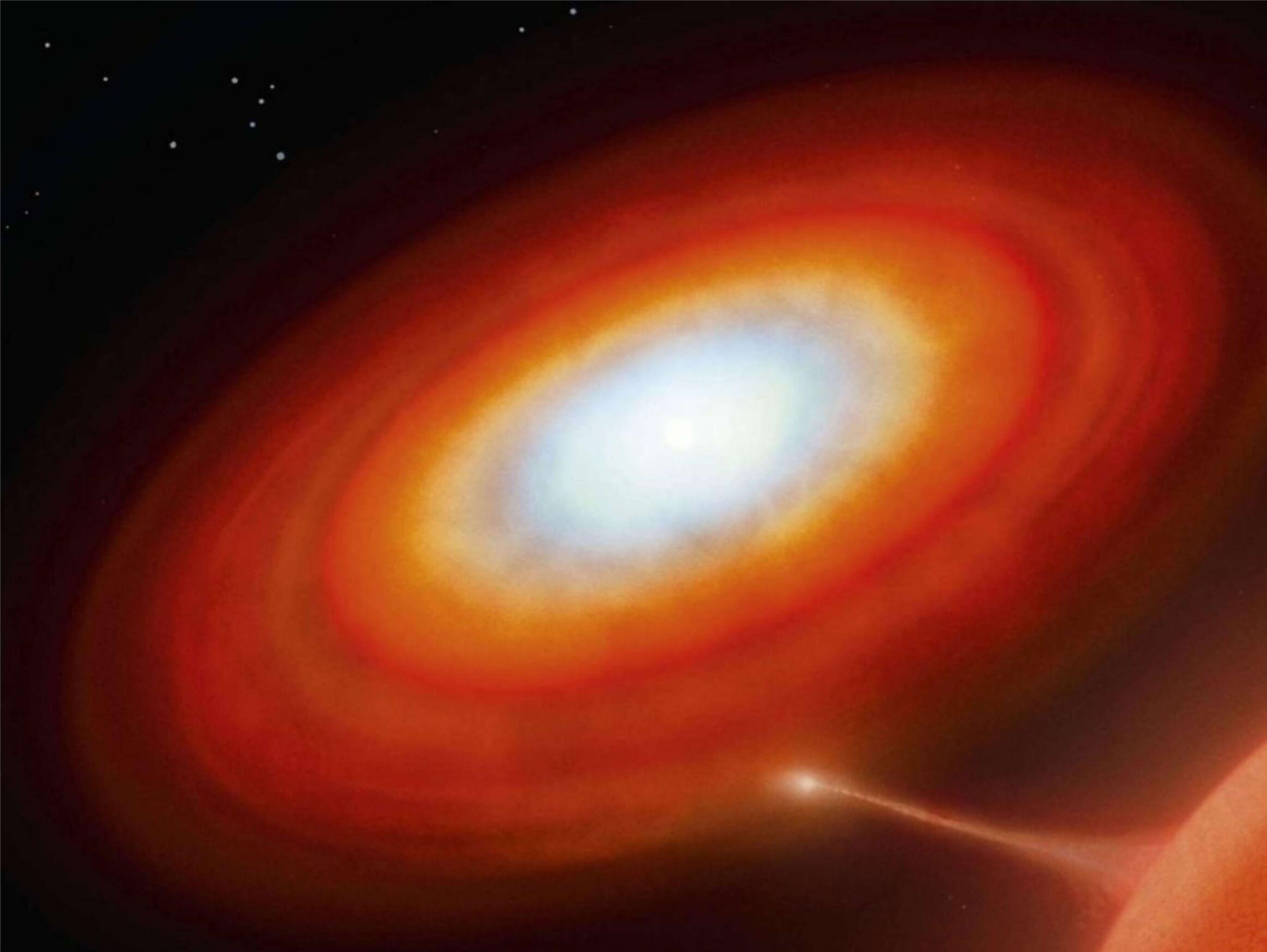
A nova explosion rips through the accretion disc surrounding the white dwarf and blasts the shattered disc into space, forming a glowing shell of gas surrounding both stars out to great distances. The white dwarf, too small to be seen on the scale of this image, is buried in the blue glow adjacent to its larger red partner

MARK GARLICK

IN SOME binary systems, the two stars are so close that one reaches out and touches the other in some fashion. Cataclysmic binaries are one such system, so named because the interaction often has profound and cataclysmic effects on one or both stars. Perhaps the most well-known examples are novae (singular, nova). The name, from the Latin word for 'new', originally described what was thought to be new stars appearing in the sky. In reality, a nova is what happens when a star that was previously too faint to be seen suddenly becomes tens of thousands of times brighter.

Imagine a system where two stars orbit each other every few hours; they're close enough that their separation barely amounts to a solar diameter. The larger of the two is a red dwarf: a dim main-sequence star. The smaller star is a white dwarf: a planet-sized stellar corpse. Each pulls on the other with unyielding determination, but they are playing a gravitational tug-of-war that only one can win. Acceding to the gravitational demands of its cannibalistic partner, the red dwarf's atmosphere is drawn towards the white dwarf – billions of tonnes of gas are pulled into orbit around the compact star to form a glowing ring of plasma spanning half a solar radius. Gradually, the ring thickens and forms an accretion disc that reaches all the way in to the surface of the white dwarf, where the gas begins to accumulate. Eventually, temperatures, pressures and densities on the surface reach such extremes that a thermonuclear reaction is ignited, the same reaction that occurs at the heart of a star. When it does, a tremendous explosion rips through the accumulated gas, announcing its presence to anyone in the surrounding area. A nova is born and its light can be seen from hundreds of thousands of lightyears away.

Usually, the event is final. But in some systems the white dwarf accumulates gas some time after the initial outburst, leading to subsequent eruptions. These are recurrent novae. There are perhaps 25 to 50 nova detonations occurring every year in the Milky Way alone. ▷



MARK GARLICK

DWARF NOVAE

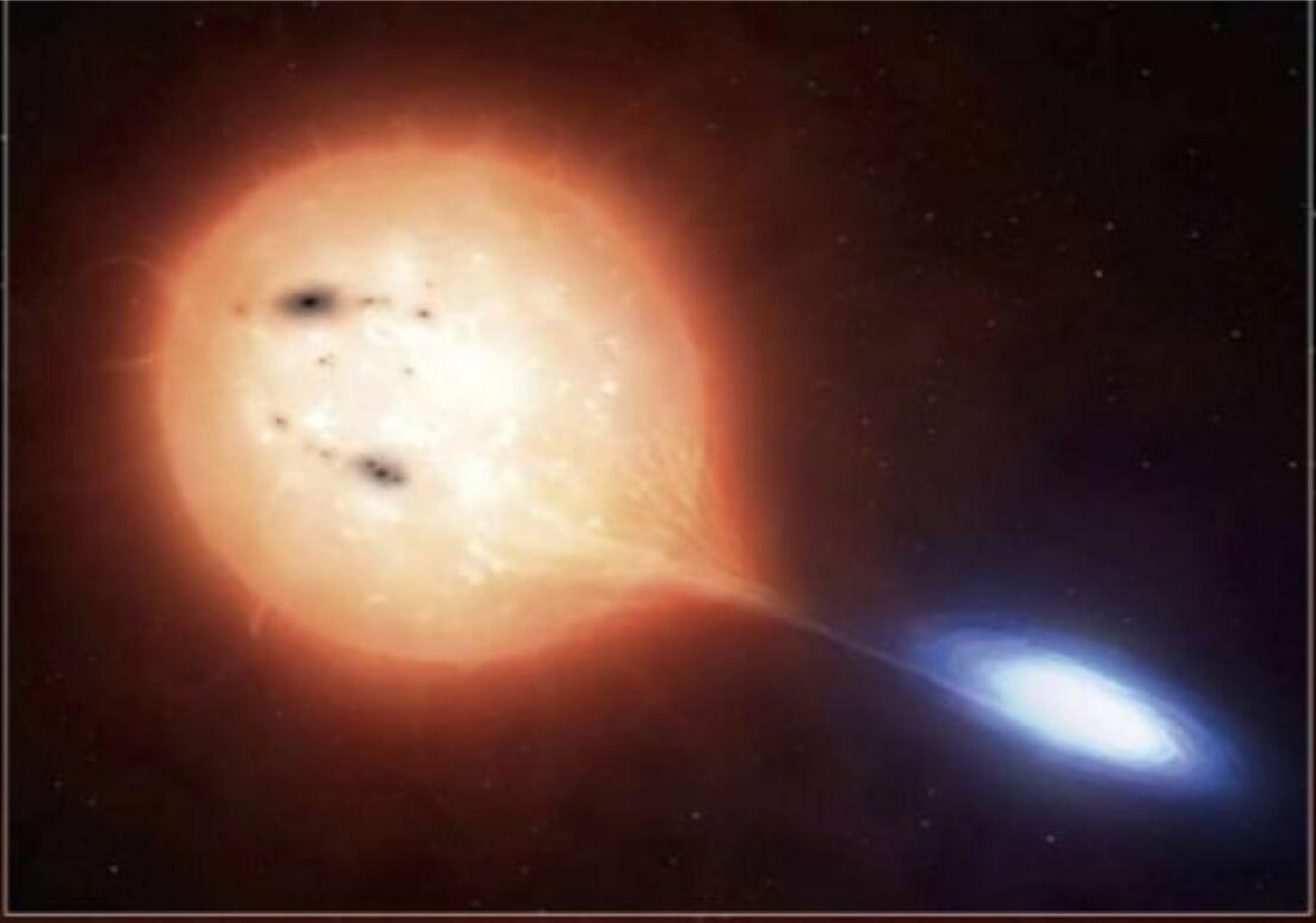
They may lack the violence of their cousins but dwarf novae make up for it with frequency

A SECOND type of cataclysmic binary, dwarf novae are slightly more sedate versions of their explosive cousins, the classical novae. As before, the phenomenon consists of a white dwarf and a red dwarf locked together under gravity. Once again, an accretion disc develops as the larger but lighter red dwarf succumbs to the pull of the hot and powerful white dwarf lying less than a solar diameter away.

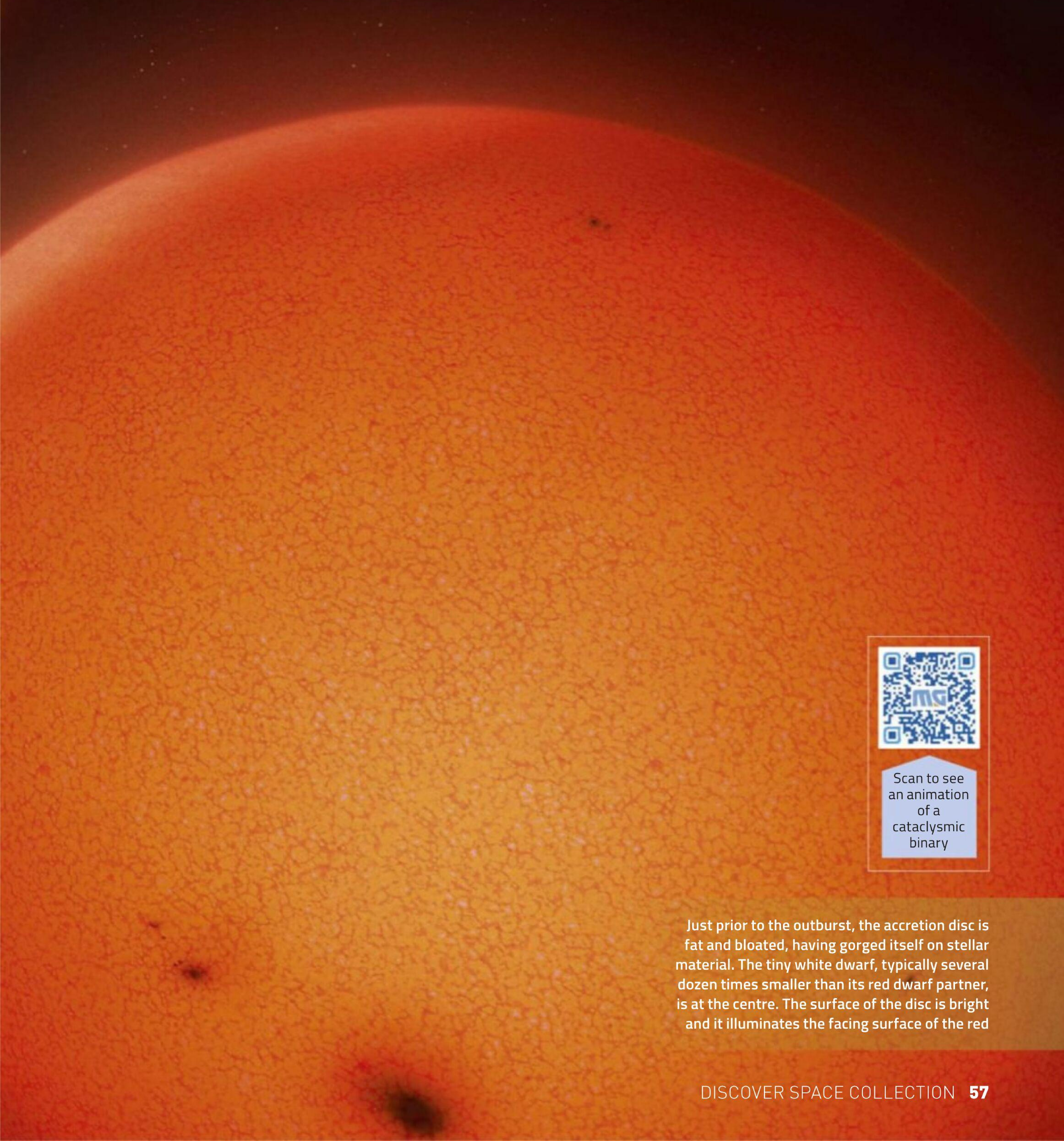
But dwarf novae differ from novae, both in the mechanism that produces the outburst and in the power of the outburst. In a classical nova, the cataclysmic eruption – the sudden, explosive and uncontained ignition of thermonuclear reactions on the surface of the white dwarf – is devastating. The accretion disc is blown to smithereens and blasted into space. But in a dwarf nova, the rapid brightening is much less violent and powerful. It's triggered a temporary increase in the rate at which material is channelled through the disc towards the white dwarf. Abruptly, with more gas plunging through the disc, it becomes larger, hotter and brighter; its luminosity flaring up by a factor of between 10 and a few hundred. That's significant, but it's still far less than in a classical nova. Once the eruption has ejected a sufficient amount of material, the accretion rate diminishes and returns to normal and the cycle begins again.

The timescale between successive dwarf nova outbursts varies, as do the durations of the events themselves. Some systems erupt every few days, while in others a wait of several decades is not uncommon. As for the outbursts, they can go on for as little as a couple of days or keep going for up to three weeks.

Although the outbursts in novae and dwarf novae are not the same, dwarf novae systems can and do experience more powerful nova explosions once enough material has been transferred to the white dwarf. ▷

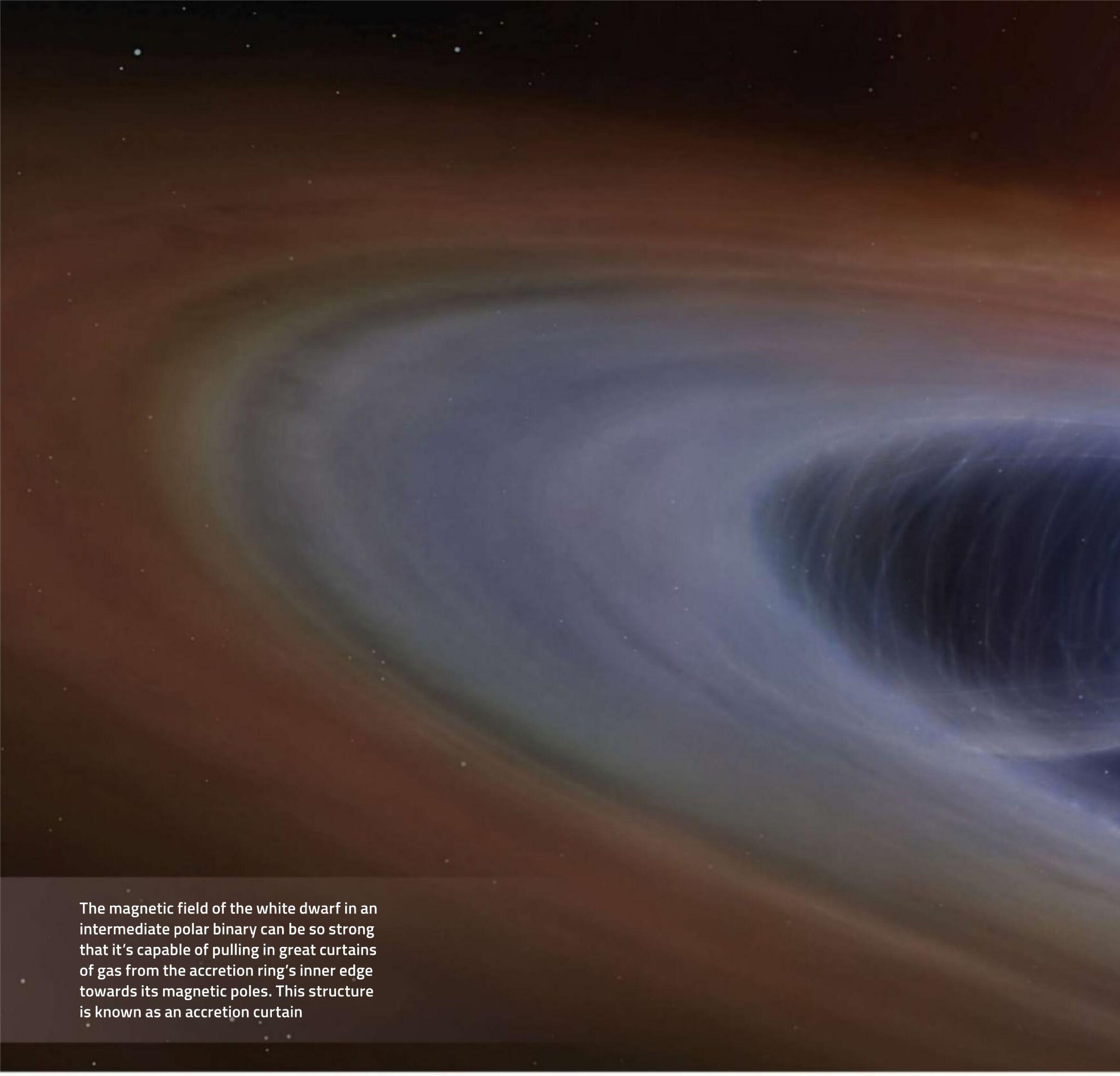


After the outburst, the accretion rate slows, and the disc becomes smaller and fainter



Scan to see an animation of a cataclysmic binary

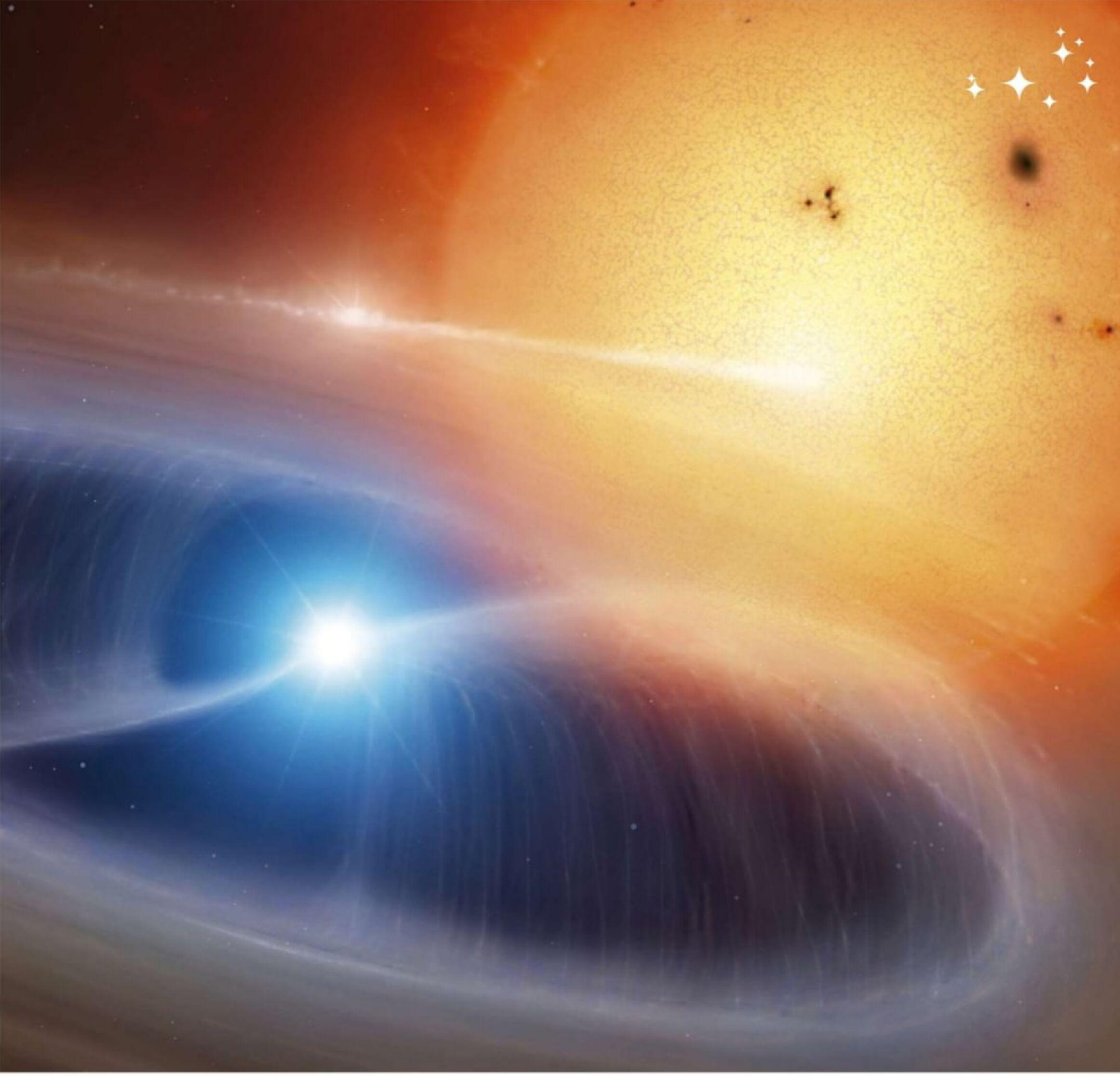
Just prior to the outburst, the accretion disc is fat and bloated, having gorged itself on stellar material. The tiny white dwarf, typically several dozen times smaller than its red dwarf partner, is at the centre. The surface of the disc is bright and it illuminates the facing surface of the red



The magnetic field of the white dwarf in an intermediate polar binary can be so strong that it's capable of pulling in great curtains of gas from the accretion ring's inner edge towards its magnetic poles. This structure is known as an accretion curtain

INTERMEDIATE POLARS

A sufficently strong magnetic field spells curtains for an accretion disc



MOST SOLITARY white dwarfs harbour a degree of magnetism, with a magnetic field strength that can be tens of thousands of times stronger than a fridge magnet. Magnetic fields also exist in the white dwarfs found in cataclysmic variables. In the subclass of cataclysmic binaries known as intermediate polars, the white dwarf has a magnetic field that can be millions of times stronger than Earth's.

The red and white dwarfs in a typical intermediate polar binary complete their orbits of each other every few hours. But while this rapid dance is occurring, the white dwarf is also spinning quickly on its axis, with periods ranging from just tens of seconds to about an hour. These attributes produce distinctive characteristics. Because the white dwarf and accretion disc are so hot, often with temperatures of up to hundreds of thousands of degrees, cataclysmic variables generally emit large amounts of high-energy radiation and are brighter at X-ray or ultraviolet wavelengths than they are in visible wavelengths. In intermediate polars, these emissions vary with the spin period of the white dwarf as well as the binary orbital period.

Intermediate polars, unlike non-magnetic cataclysmic binaries, do not have normal accretion discs. If the orbital period is fairly long – say more than four or five hours – or if the magnetic field is less than a certain value, an accretion disc will likely grow as usual, but have its centre disrupted by magnetic forces. Gas from the inner edge of the resulting ring attaches itself to the magnetic field and plummets at supersonic velocities towards the white dwarf. When it hits the star's surface, its kinetic energy converts to radiant energy and is blasted away as X-rays. If the magnetic field's strength is much higher or the binary separation is slightly tighter, the magnetic field prevents a disc from forming at all.

The intermediate polars without accretion discs share this distinction with another magnetic class of cataclysmic variable: polars. ▷

MARK GARLICK

This is an impression of a typical polar, or AM Herculis, system. The atmosphere of the red dwarf (left) slips away, flowing along a narrow stream towards the white dwarf (right). The flow is fairly straight for a while. But as it approaches the compact star, it latches onto its magnetic field and flows towards the dwarf's magnetic poles

POLARS

When a white dwarf's magnetic field gets really strong, that's when a star system's behaviour becomes truly strange

NOT LONG after astronomers unearthed the secrets of intermediate polars, a star system in Hercules started to garner attention. In 1977, researchers found another magnetic binary, but this one had a startling twist: it seemed to possess a magnetic field of phenomenal strength – 30 times greater than those found in intermediate polars and a full 100 million times the strength of Earth's. Since then, dozens of systems have been discovered with similarly strong magnetic fields. These are the AM Herculis stars, but they're also called polars because their strong magnetic fields render their light highly polarised. They form a fourth subclass of cataclysmic variable, after novae, dwarf novae and intermediate polars.

Polars display even more profound behaviour than intermediate polars. Gas slipping away from the red dwarf's atmosphere is seized by the white dwarf's powerful magnetic field. But that same field also prevents it from forming an accretion disc. So instead, the gas flows in a gigantic auroral arc from the surface of the red star along magnetic field lines to the white dwarf's magnetic poles.

But the strange behaviour doesn't end there. Imagine that the red dwarf is a ball of molasses and the white dwarf's magnetic field is made up of loops of wire, like a whisk. As the white dwarf spins, the wire loops drag through the molasses until, eventually, enough of it sticks to the whisk and the entire sticky ball starts spinning in along with it. The result is a binary system in which the white dwarf's magnetic field becomes permanently lodged in the atmosphere of its companion so that the red dwarf corotates with the white dwarf. In the same way that the Moon keeps the same face towards Earth, each of the two stars keeps the same face towards the other, and the whole system rotates as a rigid body. ▷

MARK GARLICK

LOW-MASS X-RAY BINARIES

Swap a white dwarf for a black hole and the results are phenomenal

LET'S MOVE away from cataclysmic binaries to ponder an even more energetic class of objects: powerful X-ray sources known as X-ray binaries. In an X-ray binary, the compact star or primary (the one feeding off its larger partner, the secondary) is a neutron star or, sometimes, a black hole.

Like white dwarfs, neutron stars and black holes (see pages 44–47), are stellar carcasses left over from the deaths of initially much larger stars. But neutron stars are around 100 times smaller than white dwarfs and black holes are even smaller than that, making X-ray binaries exceptionally bright and powerful.

To understand why they're so bright and powerful, imagine a white dwarf at the centre of an accretion disc. As the gas spirals around it, the disc gathers momentum and gets hotter – its kinetic energy increases. When the disc finally hits the white dwarf, the gas halts abruptly and its kinetic energy is converted into light, ultraviolet radiation and sometimes X-rays.

In an X-ray binary, however, instead of a white dwarf at the centre, there lurks a neutron star or a black hole. Because these are so much smaller than white dwarfs, the material in the accretion disc can spiral much further inwards, picking up far more speed and heat before it encounters the body at the centre. As a result, the energy released in an X-ray binary is truly phenomenal. A typical system emits as much energy in X-rays alone as hundreds, or even thousands, of Sun-like stars combined.

X-ray binaries come in two varieties depending on the secondary star. If the secondary is lightweight, similar to the Sun or smaller, then the system is called a low-mass X-ray binary. Often, the secondary in a low-mass X-ray binary is a red dwarf. If the secondary is massive, much greater in terms of mass and size than the Sun, then it's classed as a high-mass X-ray binary. ▷

MARK GARLICK

Because the secondary star in a low-mass X-ray binary is relatively small and hugs its compact companion closely, some of these binary systems could easily be contained within our Sun. Visually, they look a lot like cataclysmic binaries.

A blue giant orbits a tiny, dense companion that's either a neutron star or a black hole. The latter is buried in the midst of the bow-shaped flow of plasma that surrounds it

Scan to see an animation of a high-mass X-ray binary

HIGH-MASS X-RAY BINARIES

When distances are too great for gravity to work, that's when the stellar wind steps in

HIGH-MASS X-RAY binaries dwarf their low-mass cousins. These systems typically comprise a neutron star or black hole being orbitted by a star that's at least 10 times more massive than the Sun.

Often, the secondary star in a high-mass X-ray binary is a blue giant: a very powerful, massive star with a strong stellar wind (a steady stream of subatomic particles flowing away from the star's atmosphere and into space). Although the giant stars in some high-mass X-ray binaries may lose material to their greedy partners via the accretion disc, this does not always occur. Indeed, often there is no disc at all, for the black hole or neutron star may be too far from its cohort to strip it of gas. Nevertheless, mass transfer still takes place, courtesy of the giant star's stellar wind. Flowing radially outwards into space in all directions, some of the stellar wind encounters the neutron star or the black hole. There, like water rippling around a stone in a stream, the flowing gas wraps around the compact object and a wake forms around it – a bow shock. As the gas is brought to an abrupt halt at the bow shock, the compact star snatches it and pulls it in, vigorously generating X-rays.

A well-known example of a high-mass X-ray binary is Cygnus X-1, famous because it was the first virtually sure detection of a black hole. Black holes can never be seen directly for the simple reason that they emit no light. But the radiation emitted by an X-ray binary from the superheated accretion matter that surrounds it means that something very small and very dense must be devouring the giant star. If it's calculated to be only a bit weightier than the Sun, it's a neutron star. But if it's much more massive, it can only be a black hole. In this way, astronomers are as certain as they can be that black holes lurk at the hearts of at least some low- and high-mass X-ray binaries. ▷

MARK GARLICK

Jets of subatomic particles, moving close to a quarter of the speed of light, spew from the centre of the accretion disc and head into deep space

MARK GARLICK

MICROQUASARS

Powerful jets of gas led to the discovery of the third type of X-ray binary

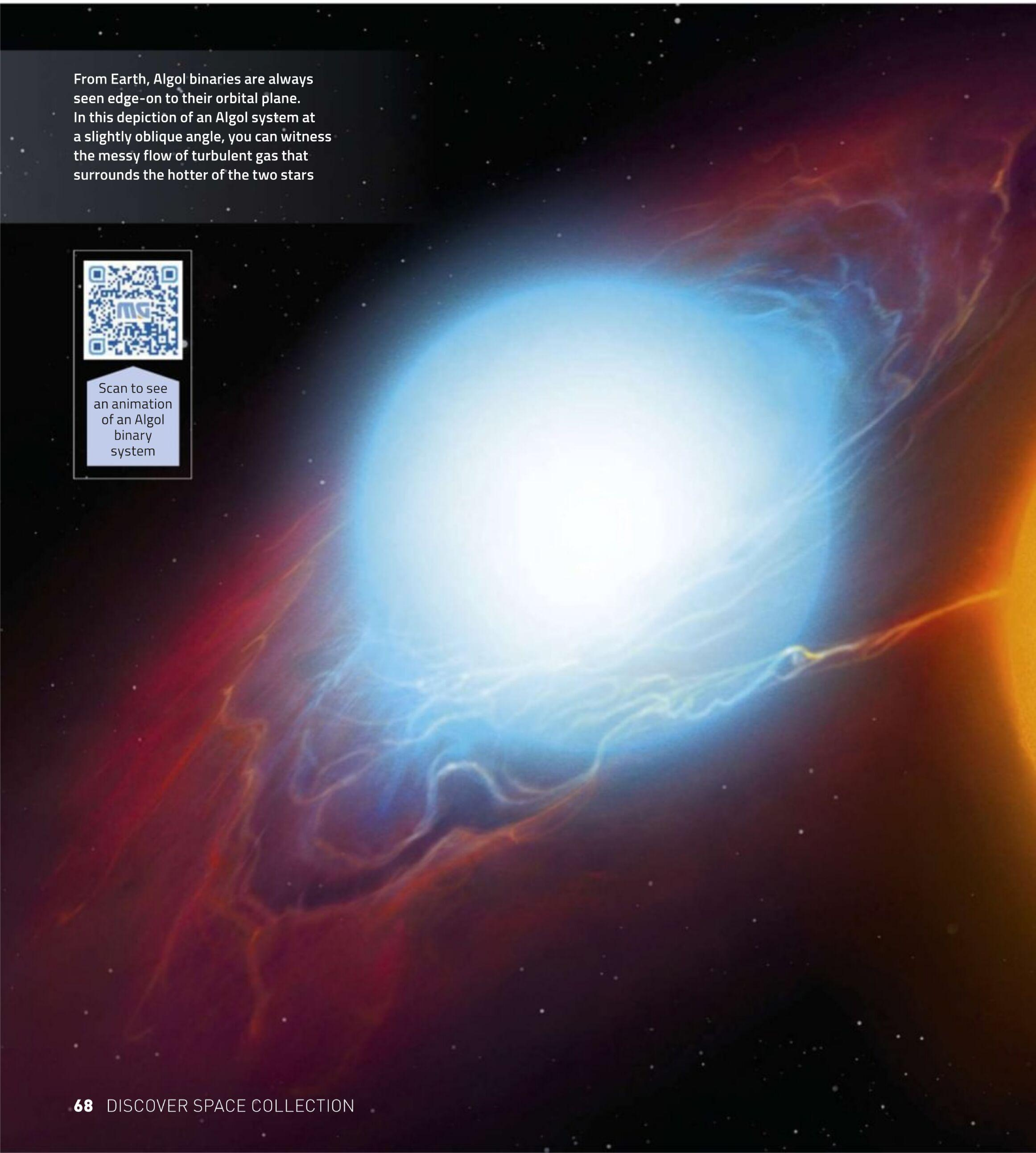
X-RAY BINARIES come in three varieties: low-mass, high-mass and microquasars. About 17,000 lightyears away in the constellation of Aquila lies a curious X-ray source known as SS433. An X-ray binary, SS433 is conspicuously bright in visible light as well as X–rays, making it an easy target for astronomical research. SS433 is unlike any other X-ray binary. What makes it different are the high-energy jets of gas that emanate from the system and plunge into deep space at almost a quarter of the speed of light. They are seen in optical, radio and X-ray bands.

In 1992, astronomers found a pair of jet powerhouses with similarities to SS433. Two more were discovered in 1994. Now, SS433 is one of a handful of X-ray binaries all emitting fast particle jets, dubbed microquasars. They were named for their similarities to quasars (see page 108). While quasars involve the cores of active galaxies, billions of lightyears away, where accretion discs surrounding supermassive black holes emit similar jets on far larger scales, microquasars are stellar in origin and much closer to home. In one system, nicknamed 'Old Faithful' after the famous geyser in America's Yellowstone National Park, the X-rays from the source blink off every half an hour, prompting the sudden appearance of radio and infrared jets. Five minutes later, the jets vanish and the X-rays reappear.

One possible explanation for this activity is that in the system, which is called GRS 1915+105, the accretion disc periodically fills up with material stolen from the bloated secondary star by the central black hole. During this time, the disc is a strong X-ray source by virtue of the power of accretion. But once it's full, after about 30 minutes, the system blasts the inner part of the disc into space. At this point, the X-rays rapidly diminish and the ejected material forms the radio and infrared jets. ▷

ALGOL SYSTEMS

The right angle and proximity leads to eclipses that are as regular as clockwork



From Earth, Algol binaries are always seen edge-on to their orbital plane. In this depiction of an Algol system at a slightly oblique angle, you can witness the messy flow of turbulent gas that surrounds the hotter of the two stars

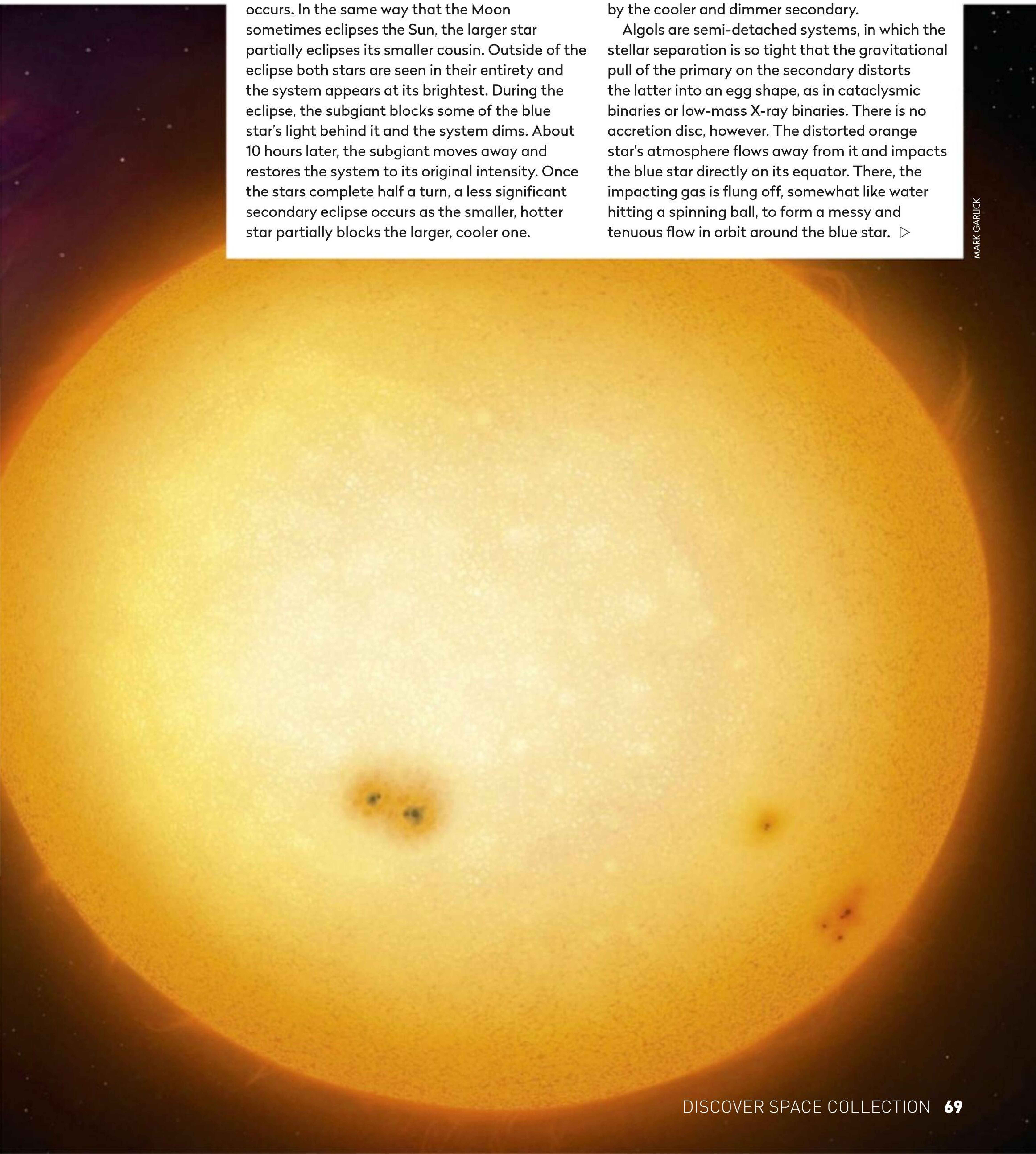
Scan to see an animation of an Algol binary system

ABOUT 93 lightyears away in the constellation of Perseus there is a famous interacting star system called Beta Persei, or Algol. The larger but dimmer of Algol's players is an orange subgiant. Its smaller partner is a blue star on the main sequence. Algol's two components swing around each other once every 2.86 days.

Seen from Earth, Algol's orbital plane is almost edge on. So, twice every 2.86 days an alignment occurs. In the same way that the Moon sometimes eclipses the Sun, the larger star partially eclipses its smaller cousin. Outside of the eclipse both stars are seen in their entirety and the system appears at its brightest. During the eclipse, the subgiant blocks some of the blue star's light behind it and the system dims. About 10 hours later, the subgiant moves away and restores the system to its original intensity. Once the stars complete half a turn, a less significant secondary eclipse occurs as the smaller, hotter star partially blocks the larger, cooler one.

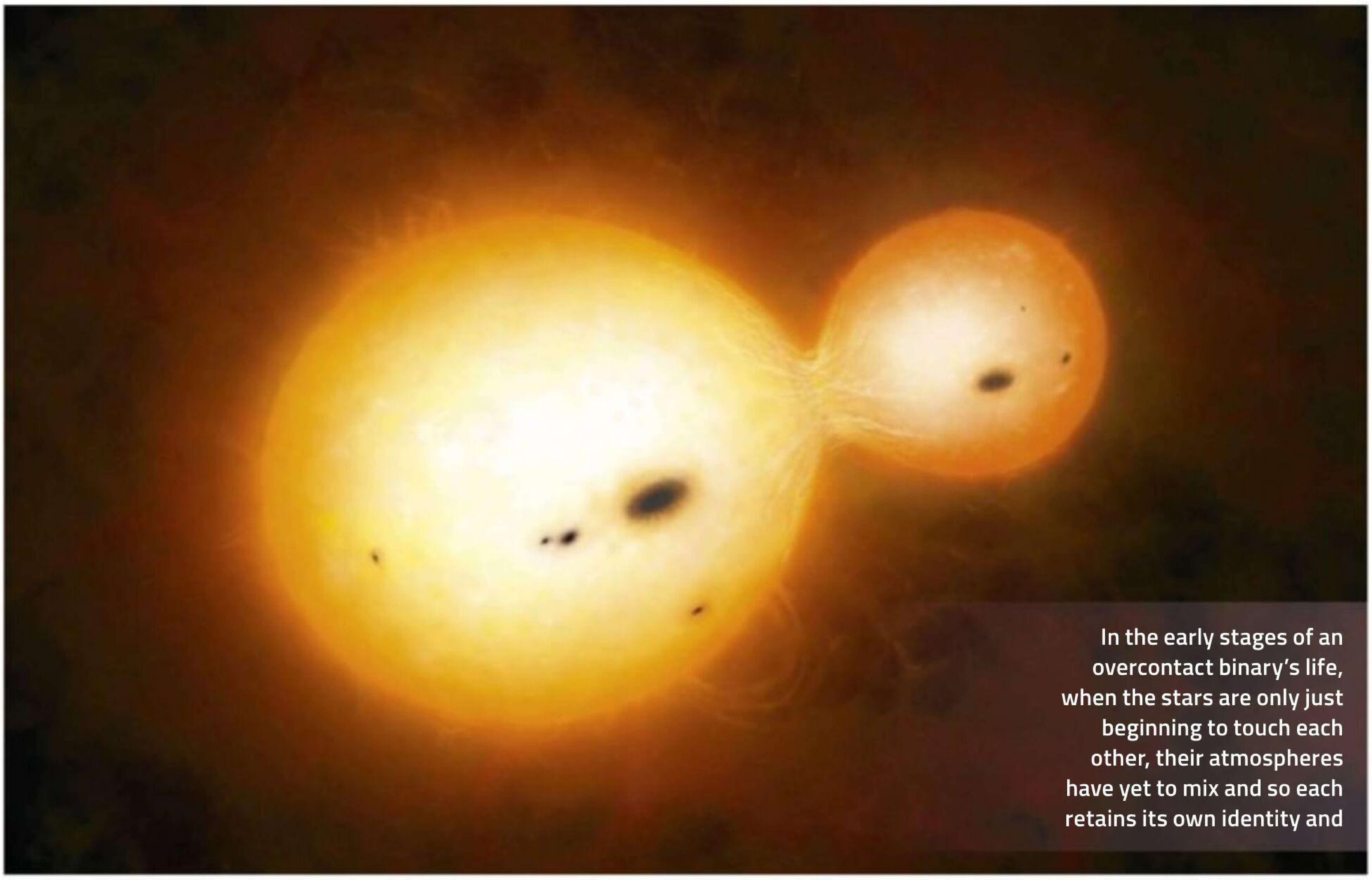
Algol is, therefore, an eclipsing binary. In fact, it was the first eclipsing binary star ever recorded, in 1669. (Cataclysmic binaries and X-ray binaries often exhibit eclipses, too.) This prototype is but one among thousands of Algol binaries that show the same behaviour: a generally constant brightness for the majority of the orbital period, then a pronounced dip in intensity attributed to an eclipse of the brighter and hotter primary star by the cooler and dimmer secondary.

Algols are semi-detached systems, in which the stellar separation is so tight that the gravitational pull of the primary on the secondary distorts the latter into an egg shape, as in cataclysmic binaries or low-mass X-ray binaries. There is no accretion disc, however. The distorted orange star's atmosphere flows away from it and impacts the blue star directly on its equator. There, the impacting gas is flung off, somewhat like water hitting a spinning ball, to form a messy and tenuous flow in orbit around the blue star. ▷



MARK GARLICK

An overcontact binary looks something like an enormous distorted dumbbell, with the two stars enveloped in a common jacket of gas that renders them the same colour



In the early stages of an overcontact binary's life, when the stars are only just beginning to touch each other, their atmospheres have yet to mix and so each retains its own identity and

Overcontact BINARIES

Two become one through distortion and absorption

SO FAR, the interacting binaries we've looked at share two common traits: one, the secondary star is almost always tidally distorted (except for high-mass X-ray binaries); and two, a bridge of glowing plasma flows from it towards the primary. But there's another class of systems where not just one but both stars are gravitationally deformed. These are often called contact binaries, but 'overcontact' is the better term.

The prototypical overcontact binary star system is W Ursae Majoris, in the constellation of Ursa Major, the Great Bear. Other binaries with the same configuration and behaviours are called W UMa stars, which are usually yellow-white to orange and are so close together that both have been stretched into an egg shape. In fact, the tidal stretching is so powerful that the two stars actually touch at the point where their gravities cancel out – the so-called Inner Lagrangian Point – and they share a common atmosphere. The mixing of the two stars' atmospheres leaves them sharing the same temperature and, as a result, the same colour, even if these characteristics were different before contact was established.

The orbital period is always less than a day, sometimes just a few hours and if you could visit the Inner Lagrangian Point, you would feel weightless, with each star pulling you in opposite directions with equal intensity.

The W UMa stars can have substantial starspots – patches blanketing areas of their surfaces. And like Algol binaries, W UMa stars exhibit eclipses as each member periodically passes in front of its associate.

W UMa binaries are the cannibals of the stellar universe. In time, the larger of the two stars completely consumes its smaller, luckless collaborator, peeling away its atmosphere, layer by layer, until only the naked core remains. That, too, is gobbled up in a final unification, and a single star exists where previously there were two. ▷

MARK GARLICK

Gliese 677 is a triple star system in Scorpius, 22 lightyears from Earth. The two central stars, 677A and 677B, orbit each other with a separation of around 12 AU. Meanwhile, a third star, 677C, orbits this pair much further out, around 230 AU away. Gliese 677C has two confirmed exoplanets in orbit around it. This illustration imagines the view from a rocky planet orbitting Gliese 677C (the large star in the sky –

Multiple SYSTEMS

Membership of star systems isn't capped at two

MARK GARLICK

AT LAST we leave binary systems to view additional stars. Like multiple births in humans, high-order stellar multiples are not common. Triple systems occur more frequently than quadruples, which in turn are more persistent than quintuple or sextuple stars, and so on. In a multiple system, the stars are usually bunched into pairs. So, in a triple there is often a close binary, with the third star orbiting much further out. Such a configuration is known as a hierarchical triple. In a quadruple star, two binary pairs orbit their common barycentre and so on.

Examples of well-known multiple stars include Castor in the constellation Gemini and Mizar in Canis Major. Each is a complicated throng of six stars. The nearest known multiple system is a triple, and it lies on our celestial doorstep. This is Alpha Centauri, or Rigil Kentaurus, one of the brightest stars in the sky.

Alpha Centauri, 4.36 lightyears away, at first appears to be a binary system. The larger star is Alpha Centauri A, which is yellow and very much like the Sun, although slightly larger and brighter. Its cohort is Alpha Centauri B, which is somewhat smaller, dimmer and more orange than its companion. Owing to their elliptical orbit around each other, the distance between A and B varies from 11.2 astronomical units (AU) to 35.6 AU. Much further away, there is the third component of this system: Proxima Centauri. Lying a little over four lightyears away, Proxima is the closest known star to the Sun. It orbits the Alpha Centauri pair at a vast distance of 13,000 AU – a meander that takes half a million years. This is so far-flung that it was initially unclear whether Proxima is in orbit around the binary at all. But the fact that all three stars are moving in the same general direction suggests they form a weakly bound triple system, and astronomers confirmed that the three stars are indeed gravitationally bound in 2017. ▷

OPEN CLUSTERS

On the far edges of the Milky Way stars are being born in quantity

CLINGING TO the spiral arms of our Galaxy are the giant molecular clouds (see page 80). Vast drifts of interstellar gas and dust, they are lightyears wide and outweigh stars millions of times to one. They're also where stars are born.

Usually, a giant molecular cloud splits up as it falls in on itself under gravity, with each of the fragments forming a separate multiple-star system or even just a single star. But in some cases, the cloud fragments are so enormous that they give birth not just to multiple stars, but entire assemblages of them, known as open clusters.

The Milky Way is estimated to contain around 1,000 open clusters, scattered randomly around its arms. They vary greatly in their size and in their contents. Some contain a few dozen stars in a region of space spanning only a few lightyears. Others are 10 times larger and boast hundreds of members. In the densest, the stars are crammed in 10,000 times more tightly than in the neighbourhood of the Sun. If our modest yellow star were in the midst of such a cluster, its nearest neighbours would be less than a third of a lightyear away, instead of 4.3 lightyears, and the night sky would be a much richer place.

Open clusters do not last forever, though. As a cluster moves around the Galaxy, encounters with other stars, other clusters and other nebulae stretch and distort the cluster, wrenching free some of its stars. While some clusters are billions of years old, in general they rarely last that long.

A famous and beautiful example of an open cluster is the Pleiades, or Seven Sisters, in the constellation of Taurus. The Pleiades cluster, easily visible to the naked eye even from a light-polluted city, is about 13 lightyears across, houses perhaps 1,000 stars and is believed to have formed about 80 million years ago. ▷

A typical but fictitious open cluster of several dozen stars glitters in the depths of space like a clutch of celestial jewels. Two stars are seen up close, one red and one blue, perhaps a binary, while the other members twinkle in the background

MARK GARLICK

On an imagined planet in the globular cluster 47 Tucanae, the sky would sparkle orange with the combined light of a million geriatric Suns. The average separation is just 0.1 lightyears – so close that the Solar System barely fits between them.

MARK GARLICK

Globular CLUSTERS

Colossal, crowded and ancient, globular clusters swarm around the Milky Way

OPEN CLUSTERS are big, but they have much larger cousins, known as globular clusters. As their name suggests, these are roughly spherical in shape. They are truly enormous balls of shimmering stars – up to a million of them, crammed into a region 100 to 300 lightyears across.

Unlike open clusters, which are usually relatively young, globular clusters are ancient. They probably formed about 10 billion years ago, before even the Milky Way itself was complete. For this reason, globular clusters are made almost entirely of geriatric stars. And because stars redden as they age, this gives globular clusters an orange tinge. Another characteristic is that while open clusters stick to the spiral arms of our Galaxy, their globular counterparts lurk much further away. They surround the Milky Way – and other galaxies, too – in an enormous swarm called a halo, each of them on a highly elliptical path, greatly inclined, generally, to the plane of the Galaxy. Around 150 of them are known to orbit Milky Way alone.

The closest and brightest globular clusters are visible to the naked eye. One of them is 47 Tucanae, in the southern constellation of Tucana. It is 15,000 lightyears away and about 150 lightyears across, a glowing crowd of one million fellow stars. This cluster is famous not only for its relative brightness but also for its sheer density, which is one of the highest known. Deep in its heart, the stars are stuffed in at a concentration of about 1,000 per cubic lightyear.

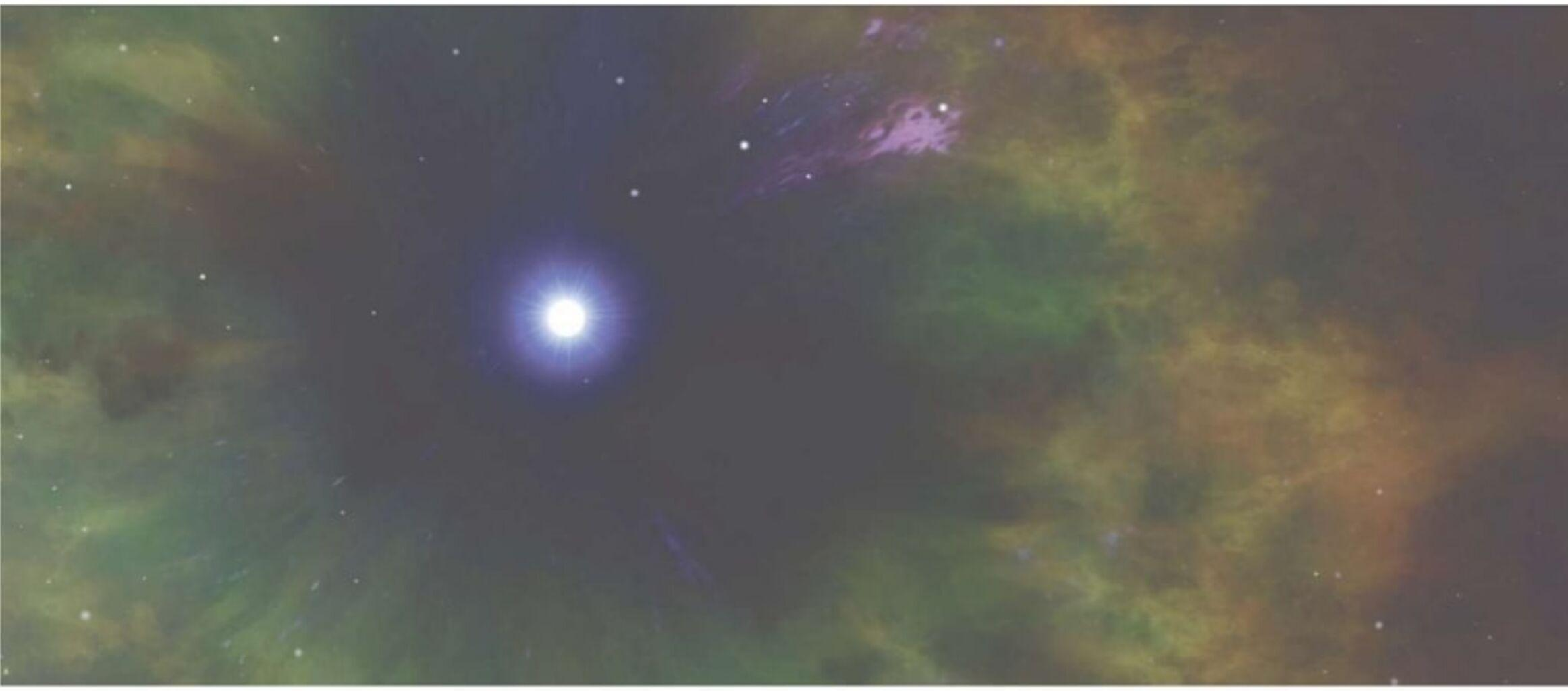
Because of this enormous density, globular clusters are not safe places for life. Supernovae explosions, when they occur, shower their nearby stars – and any associated worlds – with perilous levels of high-energy radiation. Collisions between stars are also somewhat common within globular clusters. Astronomers have found that some globular clusters contain anomalous blue stars, lost in a sea of old red ones. These objects – called blue stragglers – are believed to be the result of stellar collisions, or they may be caused by the merging of two stars in a former close binary to form a single, hot star.

INTERSTELLAR FOG

FOR AS long as we have had an interest in the skies we have known about nebulae. It's a word that comes from the Latin for 'cloud'. Initially, people used the term to describe any objects in space that looked a bit diffuse, either to the naked eye or with an optical aid. But as our understanding of physics and the Universe improved – and as the instruments at our disposal grew ever more complex, specialised and reliable – we came to realise that some of the blurry wisps of fog we were seeing were simply dense, previously unresolved clusters of stars, or even entire galaxies of stars beyond our own.

True nebulae, as the term is now used, are different. They are vast foggy patches of gas and dust that fill the swathes of space between the stars, in our Galaxy and in others. Collectively, they comprise what astronomers call the interstellar medium.

Nebulae are the Universe's Areas of Outstanding Natural Beauty. But what are these multicoloured sculptures of light actually for? What do they do, how do they come about and how many types are there? Nebulae are intimately linked to star formation and star death. Some are factories, bursting with the raw materials to create new stars. Others are cosmic graveyards, the shattered remains of stars that once were. They can be vividly luminous, energised by the light of nearby stars or they may emit no visible radiation at all. And like the stars, nebulae exhibit staggering variations in size, mass and density. ▷



MARK GARLICK

MOLECULAR CLOUDS: STELLAR NURSERIES

The colossal clouds where stars are born shroud their births in darkness

PERHAPS THE most important components of the interstellar medium are the molecular clouds. Dark, brooding and utterly frigid at temperatures around -260°C, they are perfect breeding grounds for stars and the planets that form alongside them.

As the name suggests, molecular clouds are overwhelmingly composed of molecular hydrogen – a gas in which hydrogen atoms are welded together in pairs to form a simple molecule. Molecular hydrogen, or H_2, makes up around 88 per cent of the mass of a typical cloud, with helium and trace gases making up another 11 per cent. The remaining one per cent is accounted for by so-called dust. But don't make the mistake of thinking that this is the same stuff that accumulates on your bookcases and picture frames. Interstellar dust grains are far smaller, usually less than a thousandth of a millimetre across, and composed of silicates or rocky substances. With dimensions such as these, they're comparable in size to the wavelengths of visible light and, as such, are very good at blocking its passage. Thus molecular clouds are dark, emitting no visible radiation.

But if that's the case, how can astronomers spot them? Well, molecular clouds show up as black patches when silhouetted against a brighter background. The Coalsack Nebula in the southern hemisphere is a classic example, as are the pillars of the famous Eagle Nebula, shown here. And if, as is often the case, stars are embedded within these clouds, the dust grains absorb the light and warm up, emitting detectable infrared radiation.

Molecular clouds are highly irregular, often assuming winding, serpentine shapes as a result of internal turbulence. The smallest ones are only 15 or so lightyears across, with the mass of around a dozen stars. These are called globules. But most molecular clouds are giants, spanning hundreds of lightyears with enough material crammed inside to make a million stars like the Sun. ▷

MARK GARLICK

This portion of the Eagle Nebula was made famous by a Hubble Space Telescope image. The towers, which span several lightyears and were dubbed the 'Pillars of Creation', are classic molecular clouds, inside which stars are being made

Protoplanetary discs like these are nurseries. Inside the dusty, pancake-shaped cocoons, hewn from initially much larger molecular clouds, violent processes are occurring that will one day create entirely new stars and planetary systems

MARK GARLICK

PROTOPLANETARY DISCS:
PLANETARY NURSERIES

Out of vast swirling clouds of dust and gas, solar systems start to take shape

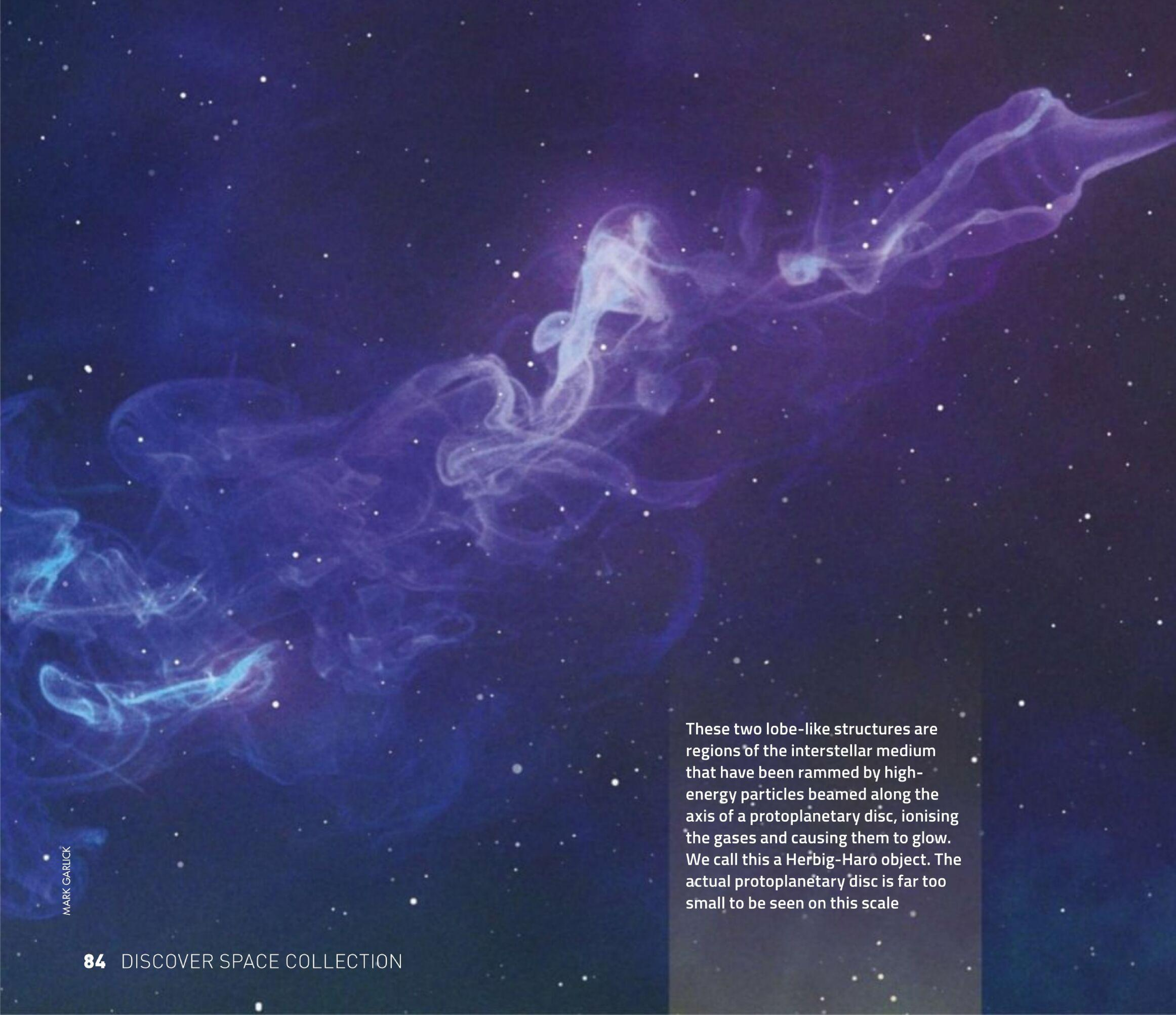
JUST LIKE the clouds you see on Earth, the molecular clouds that float in space are irregular in shape and density. In some places, they are wispy thin; in others, areas known as molecular cores, they can be much more substantial. And if the density exceeds a certain level, the molecular core begins to fall in on itself under gravity. It becomes denser and smaller, rotating faster as it does so and flattening out as a result. After about 100,000 years of this process, the molecular core becomes a gargantuan, opaque vortex of swirling gas and interstellar dust. This is a protoplanetary disc, or proplyd.

Proplyds are typically around 1,000 astronomical units across. That's about 17 times the diameter of Neptune's orbit. On their edges, they can be very cold, well below the freezing point of water. But in their central regions, where velocities, densities and friction are all much higher, temperatures can exceed 1,000°C. This leads to the formation of a protostar at the very centre (see page 28), rocky planetesimals a little further out and gaseous and icy planetesimals on the edges – a process that's known as the nebular theory of planetary formation. Indeed, the proplyd from which the Sun and its planets are believed to have been born is called the Solar Nebula. The theory neatly explains why stars end up in the middle and why the planets form further out. It also tells us how planets come to orbit in the same direction, spin in the same direction and orbit in the same plane.

Astronomers have discovered several proplyds in our Galaxy, the oldest being around 25 million years old. In 1993, the Hubble Space Telescope famously zoomed in on a tiny portion of the Orion Nebula and found four stars within it still surrounded by protoplanetary discs, adding considerable weight to the nebular theory of planetary formation. ▷

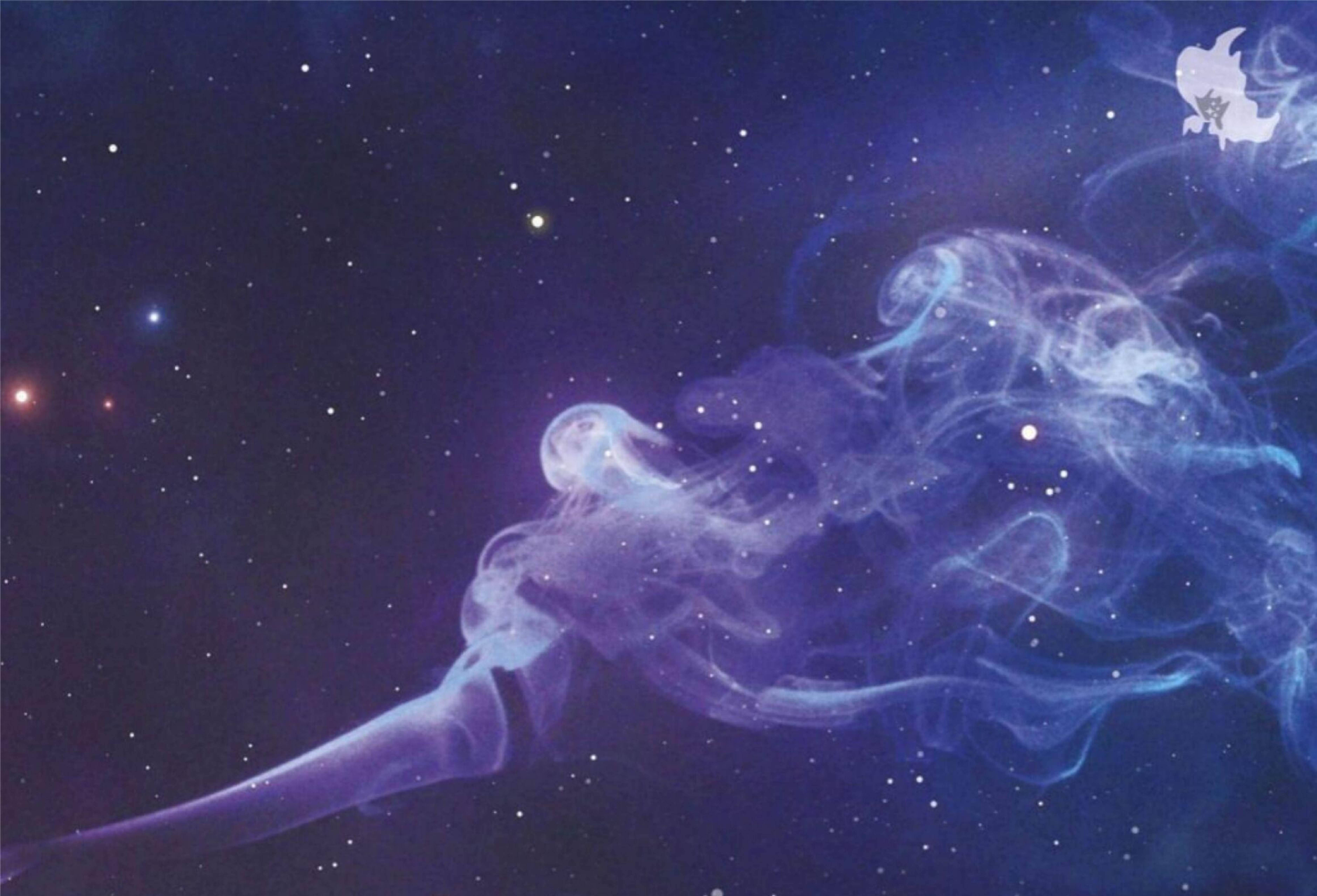
HERBIG-HARO OBJECTS: STELLAR SHOCKWAVES

Collisions between high-energy jets of plasma and clouds of dust and gas produce light-shows that span vast distances



These two lobe-like structures are regions of the interstellar medium that have been rammed by high-energy particles beamed along the axis of a protoplanetary disc, ionising the gases and causing them to glow. We call this a Herbig-Haro object. The actual protoplanetary disc is far too small to be seen on this scale

MARK GARLICK



YOU CAN'T talk about protoplanetary discs without mentioning the odd-sounding Herbig-Haro objects, a phenomenon named after the two astronomers (George Herbig and Guillermo Haro) who first studied them in detail in the 1940s.

Via a mechanism that researchers still do not fully understand, but probably involving magnetic fields, some protoplanetary discs emit powerful beams of subatomic particles, called polar jets. Hurtling outwards from the centre of the disc at speeds of several hundred kilometres a second and running parallel to the disc's spin axis, the jets collide violently with surrounding gases and create shockwaves that ionise them.

Ionisation is the process whereby a neutral atom (consisting of a positive nucleus surrounded by negative electrons) is broken apart. The fragments are called ions. Once ionised, the gas (now properly called a plasma) is in a high-energy state that is inherently unstable. This is because positive and negative ions, having opposite electric charges, tend to attract. So the ions in a plasma are constantly trying to recombine. When they manage it, light is emitted. The consequence of all this is that, in response to the onslaught of ionising shockwaves, the gases through which the particle beams travel will ceaselessly ionise and then recombine, emitting beautiful displays of colour. We observe the phenomenon as a Herbig-Haro object, or a HH object for short.

HH objects are a type of emission nebula (see page 86). They resemble long, knotty, turbulent clouds terminating in lobes and can stretch across enormous distances – sometimes as much as a few lightyears. The gases within them are typically heated to temperatures approaching 12,000°C and can weigh anything up to 20 times as much as the Earth. Around 500 of them are currently known but these nebulae are so ubiquitous in star-forming regions that their actual numbers in our Galaxy alone are likely to be 300 times greater. The others are simply too far away to be seen. ▷

MARK GARLICK

EMISSION NEBULAE: GLOWING PLASMAS

Cameras are crucial if we're to witness the dazzling light displays produced by ionised clouds of gas

This is the Trifid Nebula, 9,000 lightyears away in Sagittarius. The nebula is a staggering 50 lightyears across. The red glow is hydrogen alpha light, caused by the recombination of hydrogen, which is ionised by hot, young stars in the brightest part of the nebula. The dark regions are opaque molecular clouds in the foreground

EMISSION NEBULAE are those which shine by light that they themselves emit. Because molecular clouds are potential stellar factories, stars are commonly found within them. Usually these are young stars and, as such, they are prodigious sources of ultraviolet light – the same light that's responsible for sunburn, skin aging and skin cancer here on Earth.

In space, ultraviolet light ionises interstellar gases very effectively. As the ionised atoms recombine, they emit beautiful displays of colour that are the hallmark of emission nebulae. A similar process generates neon light: a high voltage passed through the tube ionises the neon gas within, which then emits light as its atoms recombine.

Gas clouds that have been ionised by ultraviolet sources in sites of star formation are known as HII regions. The name – pronounced 'H two' – simply means ionised hydrogen (it's not to be confused with H_2, though, which refers to molecular hydrogen). Examples of emission nebulae include Herbig-Haro Objects (see page 84), planetary nebulae and supernova remnants (see pages 90 and 92 respectively).

Because of the predominance of hydrogen, which emits a characteristic red light called H-alpha ($H\alpha$) when its atoms recombine, most emission nebulae are red. Other colours can be present, however, depending on the nebula's constitution and the intensity of the ionising source. If the composition is suitably varied, or if the ultraviolet radiation is powerful enough, a kaleidoscope of colours can appear.

That said, the colours we see in photos are much more vivid than they would appear to our eyes, as nebulae are too faint to trigger the cone receptors that colour our vision. Not only is photographic equipment more sensitive than our eyes to the colours in a nebula, but a camera's shutter can be left open for long periods, amplifying the light coming in and emphasising the colours. ▷

REFLECTION NEBULAE: CELESTIAL MIRRORS

The clouds of gas and dust that give the sharp light of stars a foggy glow

We stand on the surface of an imagined world orbiting a brown dwarf (right) in the Pleiades star cluster. The sky is ablaze with the combined light of the cluster's other members. A nearby cold molecular cloud catches the light of these stars and manifests itself as a reflection nebula

MARK GARLICK

MOLECULAR CLOUDS, as previously mentioned, emit no visible radiation of their own, while the warmer emission nebulae offer prodigious displays of dazzling colour as a result of intense ionisation sources nearby or within them. Occasionally, however, the stars within a nebula may not be powerful enough to ionise; or the stars may reside outside the nebula, off to one side. In these cases, we might see what's known as a reflection nebula.

Unlike emission nebulae, reflection nebulae emit no light of their own. Instead, the interstellar dust particles within them catch the light of nearby stars and bounce it back towards us, like fog around a street lamp. This reflection process – known in astrophysics as scattering – is far more efficient at short wavelengths, towards the blue end of the spectrum, so blue is scattered more readily. The same process is responsible for Earth's blue skies. In addition, most stars in and around nebulae tend to be young and, therefore, bluish. These factors conspire to rob reflection nebulae of the many colour variations that typify emission nebulae, producing instead a mostly cerulean light, which is, nevertheless, a beautiful sight to behold.

Around 500 reflection nebulae are known. Perhaps the most famous is the nebula associated with the tight star cluster called the Seven Sisters, or the Pleiades. The Pleiades is a young cluster in the constellation of Taurus, less than 100 million years old. The stars are shrouded in nebulosity that astronomers originally thought was part of the ancient molecular cloud from which the cluster formed. We now know, however, that this is an unrelated nebula in the interstellar medium, which the stars are merely traversing on their ceaseless journey around the Milky Way Galaxy. ▷

This is an example of a typical but hypothetical planetary nebula. The dying star's original core, now a white dwarf, is seen at the centre of the concentric shells of glowing gas. Off to the right is one of the planets of the original star

PLANETARY NEBULAE: DEATH SHROUDS

Stars put on an incredible light show to indicate when they're running on empty

HUNDREDS OF years ago, astronomers started to discover odd, fuzzy discs through their telescopes. Planets looked similar through these early, primitive instruments, so these objects became known as planetary nebulae. But they have nothing to do with planets. Now, with advanced observatories and with a better understanding of physics, we can appreciate these phenomena for what they truly are: the discarded envelopes of once mighty stars. They are a type of emission nebula.

When a lightweight star such as the Sun runs out of fuel, it begins to expand as a result of changes in its core. Without hydrogen, the nuclear furnace halts and the core contracts. It grows hotter and hotter until, at a certain temperature, the helium in it starts to undergo nuclear reactions. The core, alive again and dozens of times hotter than before, spews fresh energy outwards and this pushes on the star's outer layers.

Helium burning is highly dependent on temperature. So tiny changes in the core temperature equal vast changes in the reaction rate. This results in pulses rippling through the star, inflating the atmosphere even more until it detaches completely from the core. The core, now termed a white dwarf, ionises these gases and the result is a planetary nebula, one of the most beautiful light shows in the Universe.

These nebulae can take on a bewildering variety of colours and shapes. Some are simply spherical shells. But more and more are being found with intricate structures such as lobes and jets. The envelope expands at a speed of around 20-30 km/s and continues to do so for up to 50,000 years. After that time, with the nebula approaching a lightyear or so in diameter, the gases are too far from the white dwarf for effective ionisation and the nebula begins to fade.

After billions of years, the ashes of the once-brilliant star are returned to the interstellar medium where, one day, they will form the raw materials for a new generation of stars. ▷

MARK GARLICK

MARK GARLICK

SUPERNOVA REMNANTS:

SHATTERED STARSTUFF

What's left behind after a dying star blows apart is vital for the formation of subsequent generations of astronomical bodies

STARS THAT are more massive than the Sun also leave behind a nebula when then expire. But they don't go quietly. They go supernova! And in these cases, the energies and velocities involved are much more extreme than in the more sedate planetary nebulae.

When a star much more massive than the Sun reaches the end of the nuclear fuel in its core, there is a great, rapid implosion. Within a mere second, the entire core of the star, initially larger than a planet, is compressed under gravity to the size of a city. It forms a tiny stellar corpse known as a neutron star (see page 44). Even more massive stars become black holes (page 46). As a result of this implosion, shockwaves are sent outwards from the collapsing core through the surrounding stellar envelope, shredding it to pieces and throwing it into outer space at huge velocities, as much as 10 per cent of the speed of light, or 30,000 km/s. This is a supernova. So much friction is created within this expanding shell of gas that it easily reaches temperatures of millions of degrees Celsius. The result, a fractured cloud of shattered star-stuff, glowing with seething energy, is a special kind of emission nebula called a supernova remnant.

Supernovae are important for two reasons. The first is that during the initial explosion when temperatures run to extremes, nuclear reactions take place within the expanding gases that don't occur under any other conditions in the known Universe. If it were not for supernovae, iron and all the elements in the periodic table that are heavier than it would simply not exist. There is no other way for them to form. All of the iron inside your body was once forged in the furnace of a giant, dying star. The other reason why supernovae are so vital is that, like planetary nebulae, they enrich the interstellar medium. They return the gases borrowed when the star was alive to the cosmic gene pool, so that subsequent generations of stars – not to mention humans – can flourish.

Scan to see
an animation
explaining
the various
types of
supernovae

Where once shone a star, there now exists only a tangled web of shattered star-stuff known as a supernova remnant while the progenitor star's planets are left barren and sterile

GALAXIES AND BEYOND

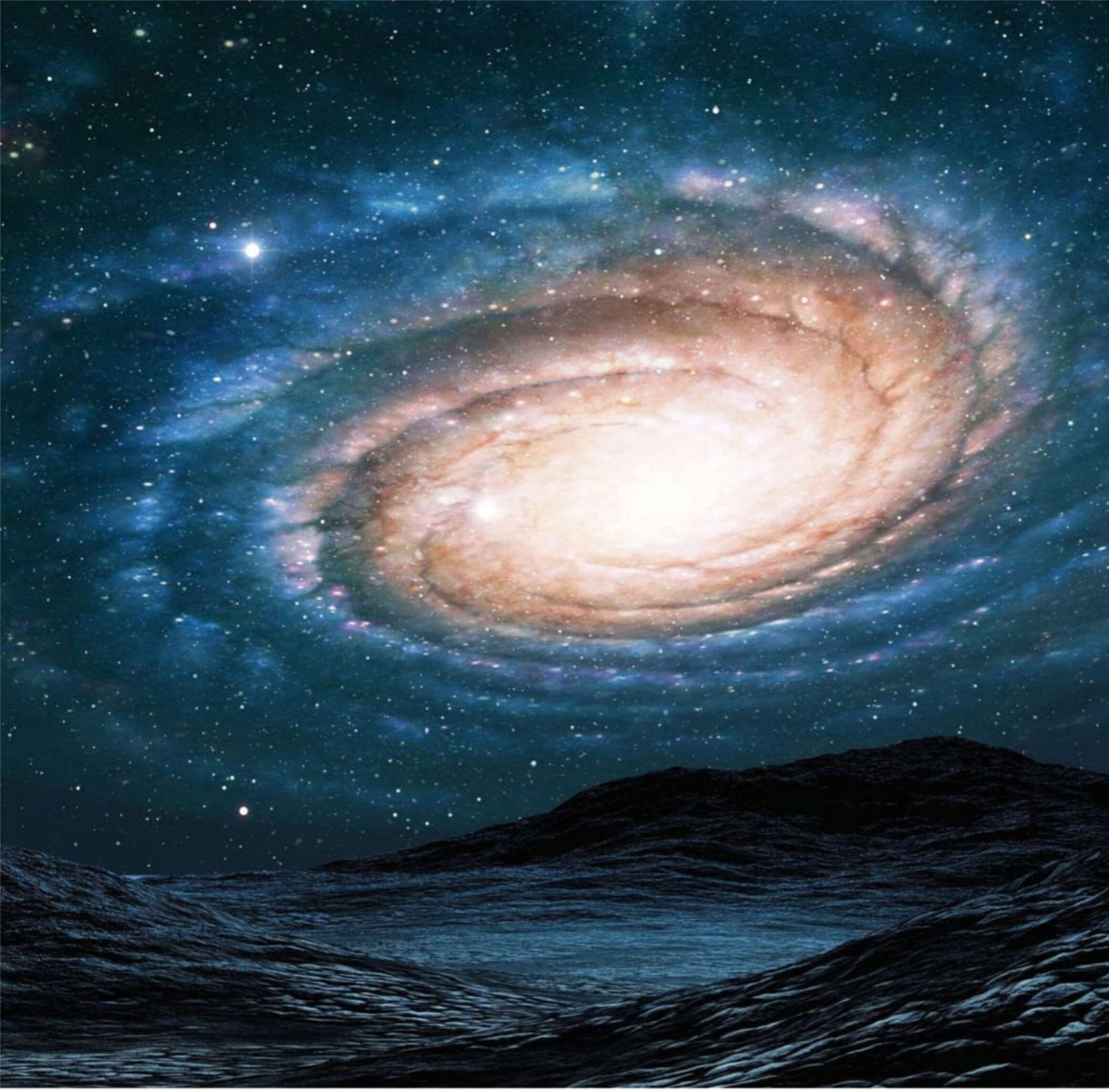
IN THE previous sections we've encountered planets, stars, star clusters and nebulae. But we've yet to see how these objects all fit together. There is incredible beauty, structure and order to the Universe. The members of the cosmos we have met so far are not randomly strewn throughout space. Instead, they belong to a gigantic collective – a super-sized construct called a galaxy. Our Galaxy, known as the Milky Way, is 100,000 lightyears wide, contains an estimated 200–400 billion stars and quite possibly even more planets. It's flat like a disc and resembles a Catherine wheel. Astronomers call it a spiral galaxy.

The Milky Way is not alone. There are billions of other galaxies spread across the Universe. Each one is a sparkling island in the dark surrounded by the sea of extragalactic space. Each carries its own cargo of planets, stars, star clusters and nebulae. Most of these alien galaxies share the spiral form of the Milky Way. But others, called ellipticals, are simply gigantic, ellipsoidal balls of stars, similar to globular clusters (see page 76) but with a thousand times their diameter and a billion times their volume. Lenticular, or lens-shaped, galaxies (see page 102) are a mixture of these two classes. Then there are irregular galaxies (see page 104), which have little, if any, coherent structure.

What lies beyond the galaxies? Well, even at these vast scales, gravity is hard at work. Its far-reaching influence bunches the galaxies into clusters, each of which contains up to thousands of members. On the largest of scales, even clusters of galaxies are subject to aggregation, being lumped into superclusters – clusters of clusters.

You can learn more about galaxy clusters and superclusters later in this section. But let's start at the lower end of the cosmic scale and examine the Universe's building blocks, the galaxies, in detail. ▷

MARK GARLICK



MARK GARLICK

SPIRALS: WHIRLPOOLS IN SPACE

A stirred up mix of gas, dust, planets and stars with a black hole at the centre

One of the most beautiful scenes imaginable in the whole Universe, the view of a spiral galaxy rising over the horizon on the surface of an alien world

WHENEVER WE think of galaxies, we likely picture majestic spirals. They are among the most complex and photogenic galaxies in existence, and they are the most common. Close to 80 per cent of all major galaxies are estimated to belong to this class, including the Milky Way.

The spiral arms are rich in nebulae, so they are active sites of star formation and therefore somewhat bluish. There are stars between the arms, but they are cooler and dimmer, giving the 'space' a darker appearance. Seen from the side, a spiral galaxy has proportions similar to two fried eggs glued back to back. At the centre is its core, or nucleus or nuclear bulge, shaped like a slightly flattened sphere. It contains mainly old stars, reddened with age, and has little active star formation. On the outskirts of the galaxy resides a spherical halo of old, red stars, many of which are confined to globular clusters (see page 76).

Like stars, planets and nebulae, galaxies vary in scale. The largest known spiral galaxy, NGC 6872, spans 522,000 lightyears and crams in hundreds of billions of stars. The Milky Way, though by no means small, is moderate at about one-fifth of that size and hosts an estimated 200 billion stars. At the other end of the scale are the dwarf spirals, which are smaller versions of their full-sized cousins at only a tenth of their size and with around a billion stars.

As we have seen, astronomers classify objects and spiral galaxies are no exception. They are given the designation SA followed by a letter a, b or c. SAa galaxies have tightly wound spiral arms and larger cores, while in SAc galaxies the spiral pattern is looser and the cores smaller. Astronomers used to think that these galaxies evolved from SAa through SAb (intermediate spirals) into SAc, but we now know that galaxy evolution is more complicated than that. ▷

This is a portrait of the barred spiral galaxy NGC 1365, seen almost face on from Earth. The bar in this galaxy is long and prominent, with spiral arms snaking out of each end. This galaxy lies 55 million lightyears away in the constellation of Fornax (the Furnace)

BARRED SPIRAL GALAXIES: THE DOMINANT SPIRALS

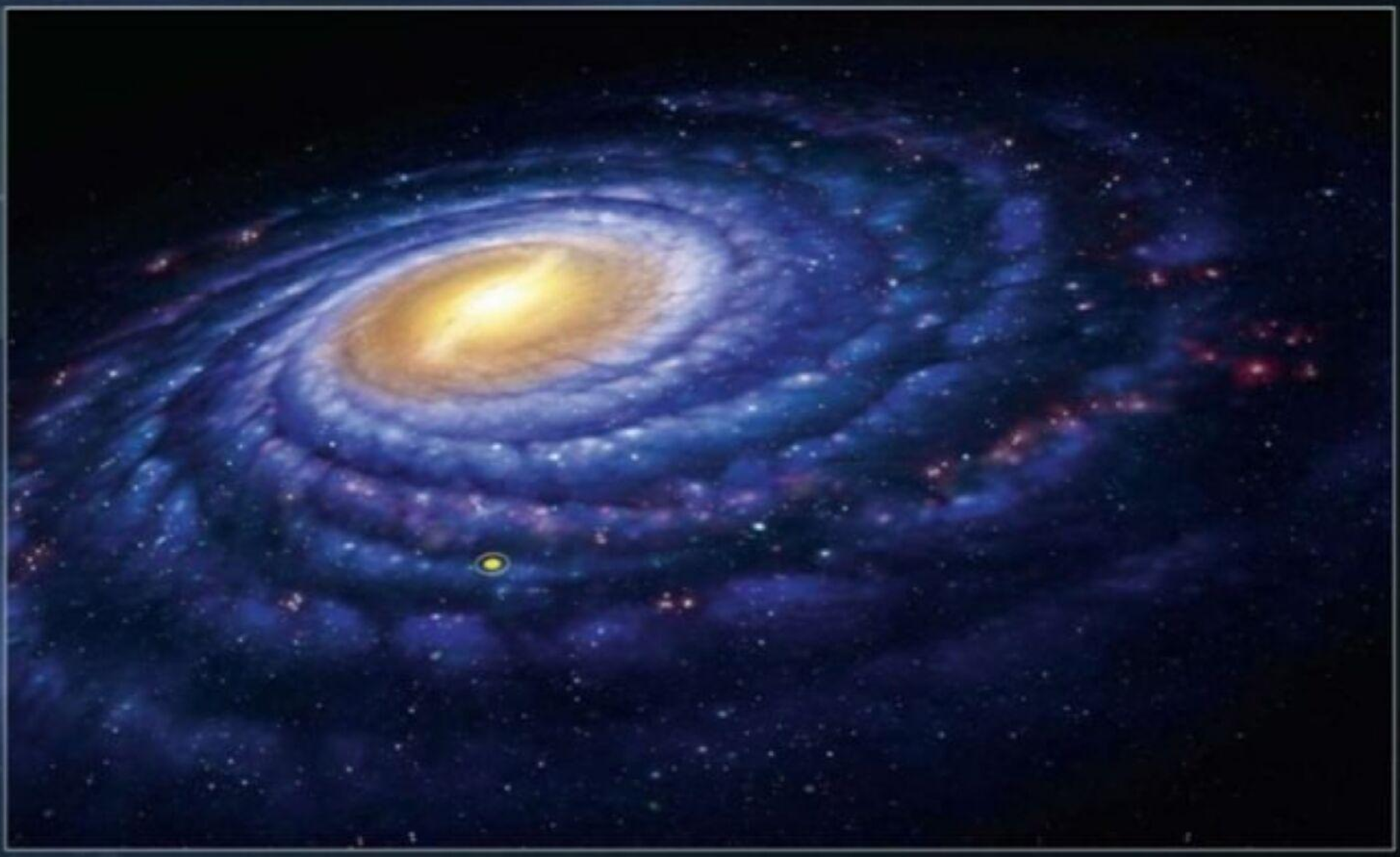
The spiral arms and nuclear bulge are present but so is another defining feature: a bar

THE MILKY Way is an example of a spiral galaxy. More precisely, it belongs to a subclass called the barred spirals. They make up more than half of all spirals, perhaps as many as two-thirds, so they are predominant.

Barred spirals are similar to their regular siblings in almost every way. Both classes have bright spiral arms encrusted with rich star-forming regions full of young stars; both have nuclear bulges filled with geriatric, reddish stars; both are flat and rotate about the central hub; and both are surrounded by halos of globular clusters, each containing up to a million individual stars. The difference is that in a barred spiral galaxy the spiral arms do not begin at the centre and wind outwards. Instead, a thick bar of stars runs through the galaxy's core, and the spiral arms are attached to either end of this bar. The length of the bar is usually two to five times its width and often it is marked with thick lanes of interstellar gas and dust where new stars are being born.

Again, as with regular spiral galaxies, astronomers have developed a classification scheme. Barred spirals with tightly wound arms and larger nuclear bulges are type SBa, while looser windings and smaller bulges earn them the designation SBb or SBc. The Milky Way, for example, is possibly classed SBb – but we cannot be certain because we are unable to see the spiral structure from the outside. Galaxies that have weak bars, intermediate between spirals (SA) and barred spirals (SB), are called SAB. Because so many spiral galaxies are barred, some astronomers think that all spiral galaxies will host bars at some point in their existence and that the bars are transient phenomena, possibly even cyclical. Whether this is true or not is presently unclear. ▷

Scan to see an animation of the Milky Way Galaxy



The Milky Way is a barred spiral galaxy of approximate class SBb, having moderately open spiral arms and a small central bar. The yellow dot indicates the location of the Solar System

MARK GARLICK X 2

ELLIPTICALS: GALACTIC FOSSILS

Gigantic and geriatric, elliptical galaxies' enormous sizes are matched by their incredible ages

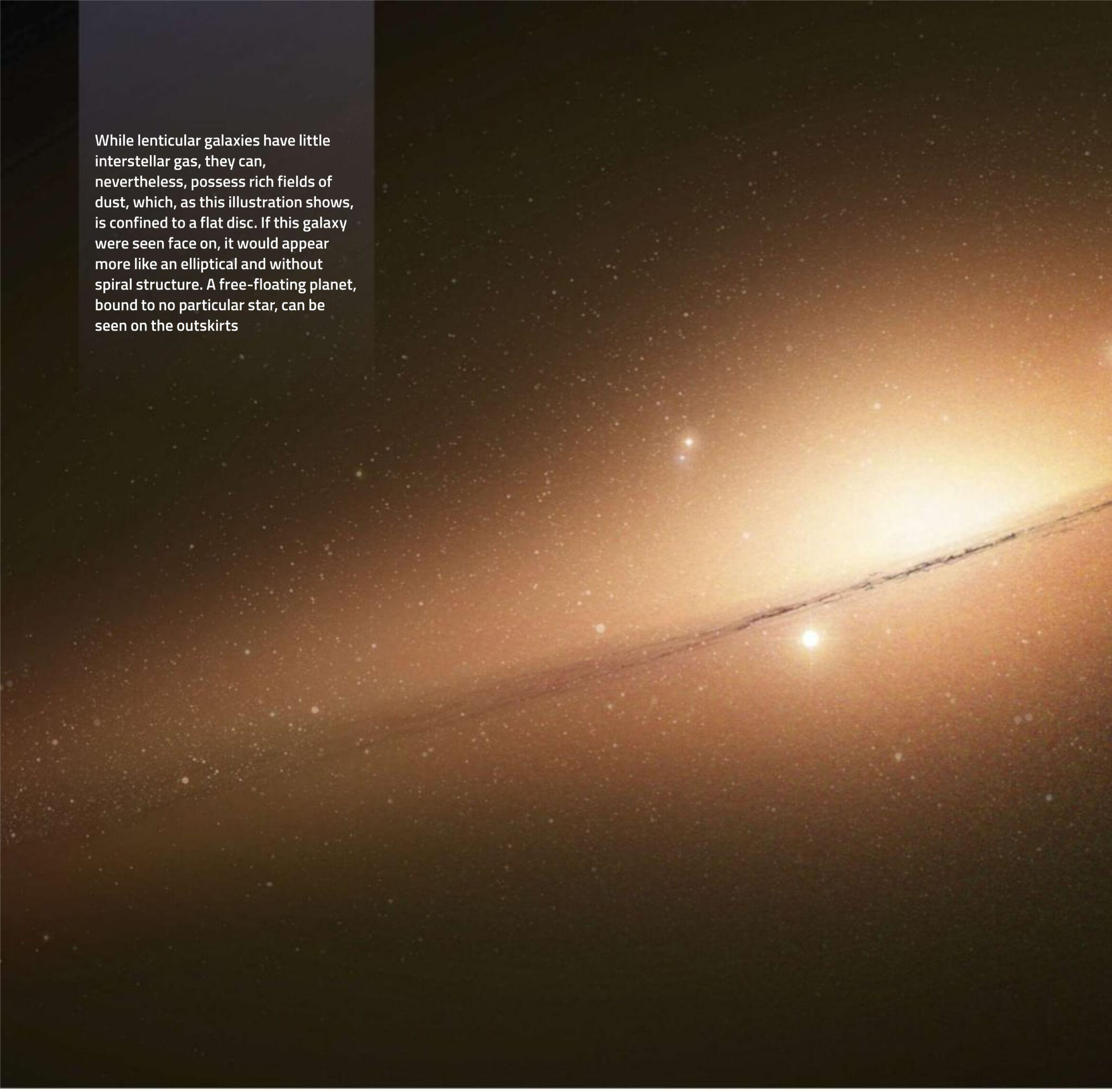
SPIRAL GALAXIES are spectacular and can be huge in terms of radius. But they are not the most massive galaxies since they are quite flat with limited volume. This is where elliptical galaxies dominate. They get their name from their appearance on the sky – they resemble fuzzy, oval blobs. What they lack in appearance they more than make up for in terms of size and mass. The largest elliptical galaxies can stretch for millions of lightyears and harbour over a trillion stars. They are the giants of extragalactic space.

Ellipticals have quite varied shapes. Some are shaped somewhat like a rugby ball or a squashed sphere. In these cases, they have cylindrical symmetry. Others are fairly spherical. In general, each of their three axes is of a different length, so their appearance will differ depending on viewing angle. As with spirals, ellipticals are subject to a classification scheme. Those that look the most circular on the sky are of type E0; the more oval they are, the higher the classification number. Galaxies of type E7 are long and cigar-shaped. The classification says little about the actual 3D shape of the galaxy, however. A galaxy of type E0, appearing circular to us in its orientation, might well be a long rugby ball when seen end on. There is no easy way to tell.

Aside from size and shape, the other big difference between elliptical and spiral galaxies is that the former have little or no molecular cloud. Recall that molecular clouds are where stars are made. So, while spirals are alive with vibrant nebulae and newly forming stars, ellipticals are almost totally devoid of young stars and star formation. They are comprised almost entirely of ancient, reddened stars, billions of years old and, like spirals, are embedded in a swarm or halo of equally old stars that are gathered into globular clusters. In a sense, elliptical galaxies are fossils. ▷

MARK GARLICK

This is an example of a special type of elliptical galaxy called a shell galaxy. It appears as an orange oval, denser towards its core, with globular clusters and a few separate stars clinging to the outskirts. Meanwhile, surrounding this are concentric shells, also full of stars. In the background are smaller, satellite galaxies, orbiting

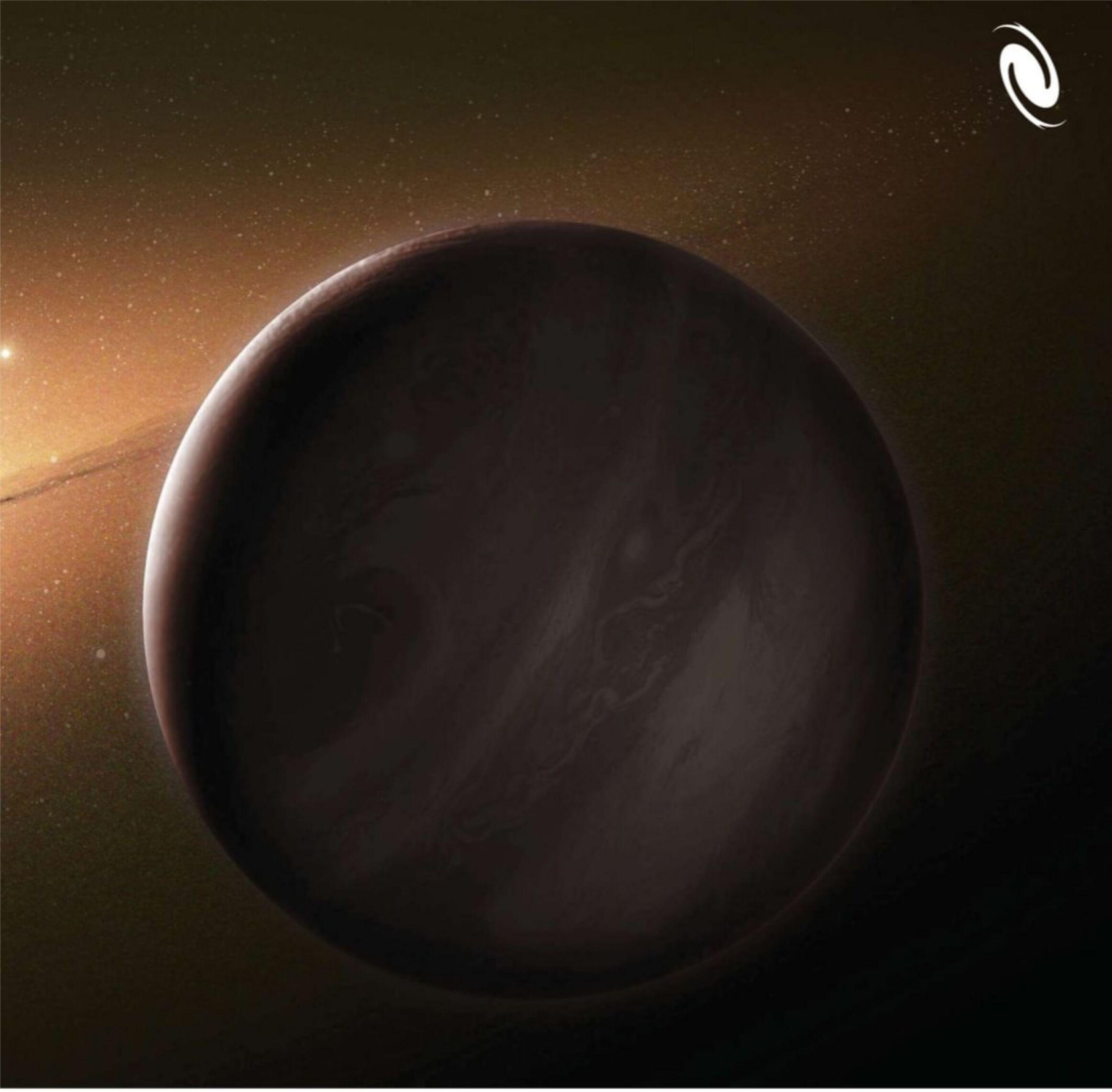


While lenticular galaxies have little interstellar gas, they can, nevertheless, possess rich fields of dust, which, as this illustration shows, is confined to a flat disc. If this galaxy were seen face on, it would appear more like an elliptical and without spiral structure. A free-floating planet, bound to no particular star, can be seen on the outskirts

MARK GARLICK

LENTICULARS: LENS-SHAPED GALAXIES

The mongrels of space blend features of spiral and elliptical galaxies



SPIRALS AND ellipticals are the most common types of galaxy, but there is another type that's a kind of hybrid of the two of them. These are known as lenticular galaxies and are classified S0. Their name comes from the fact that the original members of this class resembled optical lenses viewed from the side.

Lenticular galaxies, being the mongrels of extragalactic space, share characteristics of both their elliptical and spiral counterparts. They are disc shaped, like spirals, and can have central bars, like barred spirals, but they appear to have no discernible spiral arms. And more akin to ellipticals they contain very little interstellar gas, so they lack star-forming regions and are dominated by old, red stars, none younger than a billion years of age. They do, however, contain interstellar dust, which ellipticals tend to lack.

Some researchers interpret these facts to mean that lenticular galaxies are spiral galaxies which, having used up their cargoes of gas to make new stars, lost their spiral arms (where the star-forming nebulae reside). Support for this idea comes from the discovery of what astronomers whimsically call 'anaemic' spirals – true spiral galaxies that have faded arms, perhaps on their way to becoming lenticulars.

But there is another possible explanation. Perhaps lenticular galaxies are the result of an extragalactic pile-up – two or more galaxies that collided a long time ago and subsequently merged into a new form. It's plausible because collisions between galaxies are pretty common – much more so than they are between stars. While the stars in a typical galaxy are separated like cherries placed dozens of kilometres apart, highly unlikely to interact even with lifetimes of billions of years, the larger galaxies are scattered more like cherries that are less than a metre apart. It's a proximity that makes for a very dynamic cosmos. ▷

IRREGULAR GALAXIES: GALACTIC BLACK SHEEP

Galaxies that are neither one thing nor the other hold clues to these structures' formation and growth

This is an impression of the Large Magellanic Cloud – the largest of the Milky Way's satellites and usually classed as an irregular galaxy. Note the red nebulae where new stars are being born. The Large Magellanic Cloud is about 20,000 lightyears wide and lies 160,000 lightyears from Earth

GALAXIES THAT fit into neither of the other two major classes, ellipticals and spirals, are called 'irregular'. Despite this name, many of these extragalactic black sheep do have some sort of structure. Some of them have hints of spiral arms, or nuclear bulges that are way off centre. These are dubbed type-I irregulars, or Irr-I. Then there are those that seemingly have no organised shape or structure. They are chaotic scrambles of stars and nebulae, without symmetry, central bulges or spiral arms and each one is unique. These are the type-II irregulars (Irr-II).

Irregular galaxies are fairly common and important because they probably represent an intermediate stage in galaxy evolution or perhaps a very early one. Gravitational interactions between galaxies, by virtue of their relative proximity to each other, are responsible for all sorts of distortions. Astronomers have created computer simulations showing how two initially separate galaxies evolve and then merge as they move closer together. The results of these simulations are strikingly similar in appearance to some of the Irr-II galaxies that we know of. So, some irregular galaxies can be considered 'missing links' in the chain of evolution from spiral to lenticular and/or elliptical. Other irregulars, however, might simply be young galaxies that have not yet fully developed their structure. Quite likely, both explanations are valid.

Our own Milky Way Galaxy plays host to a whole armada of smaller satellite galaxies. Most of these are dwarf ellipticals, but a few of them are irregular, no doubt because of gravitational interactions. Two of these satellites are the Large and Small Magellanic Clouds. You can see them clearly with the naked eye from the southern hemisphere and they look like two bits of the Milky Way that have broken off. Both show hints of a spiral structure – not to the untrained eye, though – and some astronomers prefer to classify the two of them as barred spiral galaxies. ▷

MARK GARLICK

RADIO GALAXIES: COSMIC GUSHERS

High-energy emissions provide hints to the engine rooms powering galaxies

GALAXIES VARY not only in terms of their appearance, but also in terms of the range of electromagnetic radiation they emit. Among the most powerful are the so-called radio galaxies. These objects – almost always associated with elliptical galaxies – can generate as much as 100 trillion trillion trillion Watts of power. That is more than one million times as powerful as the Milky Way and much of that energy comes out in the radio region of the electromagnetic spectrum.

There is only one power source capable of driving these powerhouses: supermassive black holes (see page 46) – their gravity is so powerful that not even light can escape them. While the ordinary, stellar black holes cram the mass of 20 Suns into a sphere a few dozen kilometres across, the supermassive black holes that impel radio galaxies are in another class entirely. They can weigh as much as one billion Suns and occupy as much space as an entire planetary system. As with stellar black holes, the supermassive ones are usually surrounded by accretion discs – gargantuan pancakes of debris made from shattered star-stuff. It is this in combination with powerful magnetic fields that makes supermassive black holes so conspicuous. Subatomic particles swirling around in the disc are accelerated to near light-speed by the magnetism and emit blistering amounts of what scientists call synchrotron radiation at radio wavelengths.

The magnetic fields make radio galaxies spectacular in another way – that is, they can channel charged particles deep into extragalactic space, well beyond the host galaxy, forming long, narrow jets. These jets collide with the rarefied gas that exists between galaxies – called the extragalactic medium and analogous to the interstellar medium within galaxies – and inflate the gas to form huge, lobe-like structures that dwarf the emitting galaxy. These lobes are similar morphologically to Herbig-Haro objects (see page 84), but on much, much larger scales. ▷

MARK GARLICK

A radio galaxy, moving rapidly through the surrounding extragalactic gases, emits powerful jets of particles that plough into those gases and pump them up to form huge radio-bright lobes. The lobes are swept back by friction with the extragalactic medium, creating structures like wakes on a pond

Deep in the heart of an active galaxy is the thick, dusty accretion disc – seen edge-on – that powers a quasar. Produced via a mechanism still not fully understood, powerful jets of charged particles shoot out of the centre of the disc and head tens of thousands of lightyears into extragalactic space

MARK GARLICK

QUASARS:
AT THE EDGE OF THE UNIVERSE

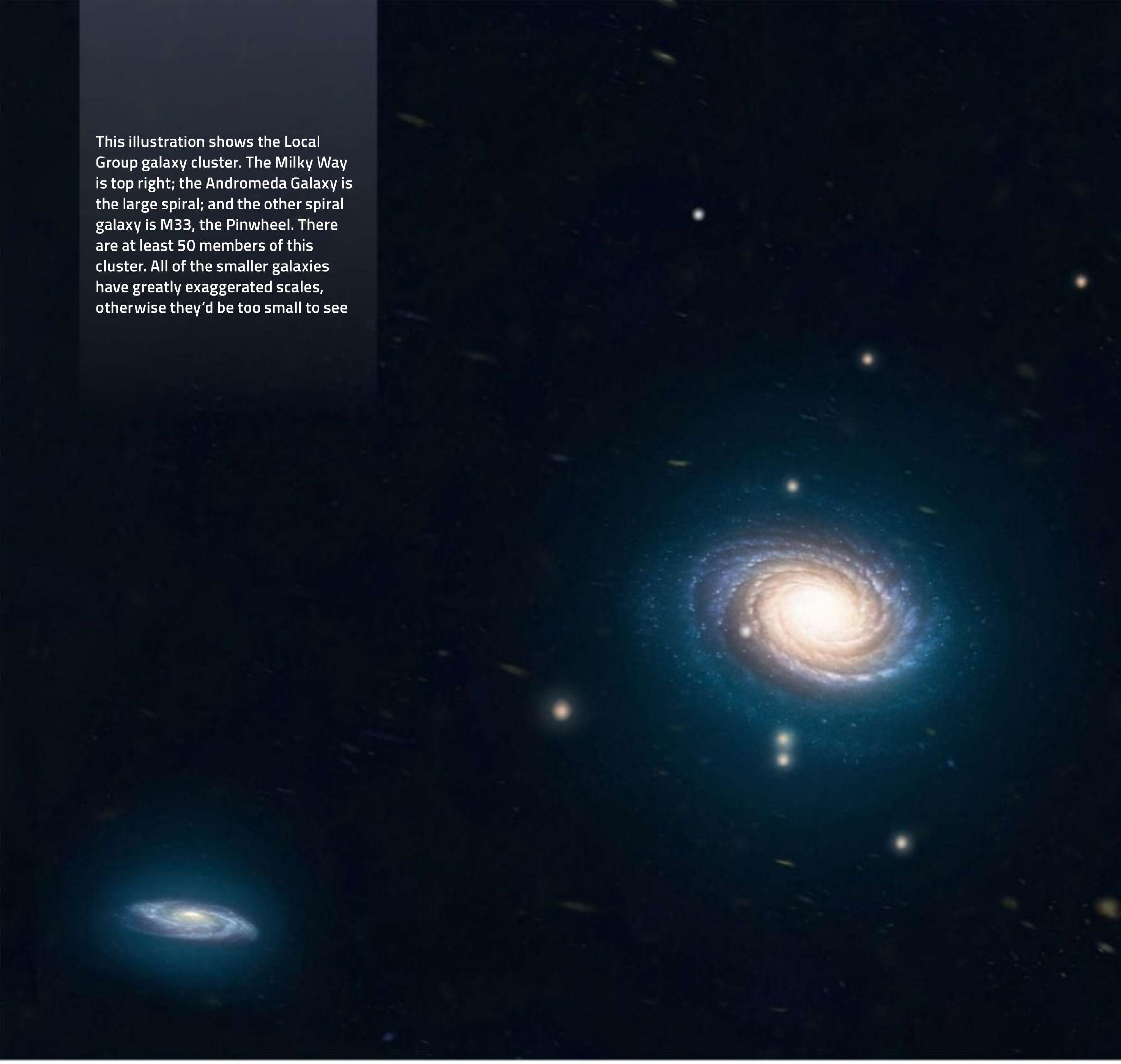
Distant and mysterious, these astonishingly powerful objects have effects that are almost impossible to ignore

RADIO GALAXIES are not the only ones in which monstrous black holes are thought to lurk. Indeed, our own Galaxy, the Milky Way, is known to host a supermassive black hole at its heart – called Sagittarius A* – and researchers have even detected radio lobes way above our Galaxy's rotation axis. Galaxies that are brighter than usual because of supermassive black hole activity are called active galaxies. Naturally, these include radio galaxies, but perhaps the most celebrated active galaxies are the mysterious quasars.

In the 1960s, astronomers began finding powerful radio sources that were well beyond our Milky Way. They had to be exceptionally bright, easily 100 times more powerful than a normal galaxy – otherwise, they would have been undetectable at such distances. Because they looked like stars they were dubbed QSOs (quasi-stellar radio objects – 'quasi-stellar' meaning 'star-like'). Nowadays, they are just called quasars. The first quasar found, called 3C 273, is an astounding 2.5 billion lightyears away but others are at distances exceeding 10 billion lightyears. They are among the most distant objects in the visible Universe. Yet their emissions have been measured to emanate from a region just a few astronomical units across. Most astronomers now agree that to be so far and small, and yet shine so conspicuously, quasars must be, like other active galaxies, powered by supermassive black holes.

These days, astronomers suspect that most, if not all, galaxies host these voracious parasites. Why, then, are not all galaxies strong radio emitters or as bright as quasars? The answer seems to be that, in many cases, the black holes are dormant. Their accretion discs have diminished so that they emit no particle beams or high-energy radiation. We know that interactions between galaxies cause gravitational perturbations. In very dense extragalactic regions, these perturbations can fling stars into supermassive black holes, creating fresh accretion and reigniting the high-energy emission. It is then that they flare up and another active galaxy makes its presence known. ▷

Scan to see an animation of a supermassive black hole



This illustration shows the Local Group galaxy cluster. The Milky Way is top right; the Andromeda Galaxy is the large spiral; and the other spiral galaxy is M33, the Pinwheel. There are at least 50 members of this cluster. All of the smaller galaxies have greatly exaggerated scales, otherwise they'd be too small to see

GALAXY CLUSTERS: LIVING IN GROUPS

Scan to see an animation of the Local Group galaxy cluster

Gravity's influence draws groups of galaxies together

AS UNIMAGINABLY vast as the galaxies and the supermassive black holes that power them are, there's a larger classification of objects still. These objects are known as galaxy clusters – bunches of galaxies that are held together by gravity's all-encompassing glue.

On a dark, clear night, a keen eye might be able to spot the Andromeda Galaxy. It appears as a faint, oval smudge of light in the northern-hemisphere constellation from which it gets its name. Andromeda – or M31 to use its Messier catalogue designation – is a large barred spiral galaxy, bigger than the Milky Way and lying at a distance of around 2.5 million lightyears. It is the furthest object in the Universe visible to the naked eye. Meanwhile, a slightly closer yet smaller and fainter spiral galaxy called M33, but is often referred to as the Pinwheel, lies in the constellation of Triangulum.

The Milky Way, Andromeda and the Pinwheel galaxies are the three biggest members of a galaxy cluster known as the Local Group. All the other participants of this group – more than 54 in total – are dwarf galaxies that mostly measure no more than a few thousand lightyears across (tiny when compared to 100,000 lightyears for the Milky Way). In total, the Local Group encompasses a region of extragalactic space that measures approximately 10 million lightyears and weighs more than one trillion Suns.

That sounds impressive, yet the Local Group, with only three major galaxies, is puny compared to some galaxy clusters. A particularly massive example, whose centre lies about 320 million lightyears from the Milky Way, is the Coma cluster. Coma contains at least a thousand galaxies, including many spirals and giant ellipticals – the latter dominating its central regions. Countless other galaxy clusters exist at sizes between Coma and the Local Group.

The space between galaxies in a cluster is not empty. It is filled with an extragalactic medium called intracluster gas. Although it is extremely sparse, this gas exists at very high temperatures and is a powerful source of X-rays. ▷

MARK GARLICK

On the very largest of scales, the Universe takes on a web-like appearance. Here, the white blobs are not stars; they are large galaxies or, more often, entire clusters of galaxies. Notice how they string together in long chains. These are superclusters, and between them are the dark, nearly spherical voids

LARGE-SCALE STRUCTURE: SUPERCLUSTERS AND VOIDS

Groups of galaxies gather together on a truly unimaginable scale

THERE SEEMS to be no end to the structure of the Universe and no limit to the force of gravity. Its influence can link objects together on truly mind-boggling scales. Stars are grouped into galaxies; galaxies are combined into clusters; and, incredibly, galaxy clusters are subject to even larger aggregations. These are called superclusters – clusters of clusters of galaxies.

Just as the Milky Way belongs to the Local Group of galaxies, so the Local Group is but one of at least 100 galaxy clusters that comprise the so-called Local Supercluster. Also called the Virgo Supercluster because many of its galaxies reside in the Virgo constellation, it stretches across a phenomenal 110 million lightyears and houses tens of thousands of individual galaxies. It is somewhat flat, shaped like an ellipse. The Local Supercluster is just one of millions of superclusters in the known Universe.

On the largest scales, the Universe has a somewhat frothy appearance. The superclusters tend to chain together to create filamentary constructs. Meanwhile, between these delicate threads are regions almost entirely devoid of galaxies, known appropriately as voids. They are roughly spherical and can stretch across 200 million lightyears. That's 200 million lightyears in which there is next to no visible matter whatsoever. On these scales, the Universe appears to be mostly empty.

This is, of course, an illusion. For the Universe is brimming with planets, stars, nebulae, galaxies and clusters of galaxies. In total, astronomers estimate that there are as many galaxies in the Universe as there are stars in the Milky Way – around 200 billion galaxies, totalling 40 billion trillion stars. That's a lot of stars. Given that many stars seem to host several exoplanets, the total number of planets in the depths of the cosmos is likely to be higher still. To paraphrase Jodie Foster's character in the movie *Contact* (1997), if we are the only life forms in the Universe, it would be an awful waste of space.

MARK GARLICK

BBC
Sky at Night
MAGAZINE

SAVE WHEN YOU SUBSCRIBE
TO THE DIGITAL EDITION

Available from

Download on the App Store
amazon apps Available on kindle fire
GET IT ON Google play
zinio™

The perfect addition to your stargazing, *BBC Sky at Night Magazine* is your practical guide to astronomy, helping you to discover the night skies, understand the Universe around us and learn exciting techniques for using your telescope.

BBC
THE UK'S BIGGEST SELLING ASTRONOMY MAGAZINE
Sky at Night
12 SIGHTS OF CHRISTMAS
Discover Brother Guy Consolmagno's favourite festive night sky objects
BBC
Showing all month: twilight bright planets
Jupiter, Saturn and the Moon meet the Evening Star
DECEMBER 2019
Sky at Night
THE UK'S BEST SELLING ASTRONOMY MAGAZINE
12 SIGHTS OF CHRISTMAS
Discover Brother Guy Consolmagno's favourite festive night sky objects
METEOR MEMO!
Watch out for the Geminid and Ursid showers
ARABIAN NIGHTS
Find the legacy of Arabic astronomers in the stars
VOLCANOES OF VENUS
Join the search for evidence of eruptions
TAKING OFF IN 2020
Space exploration is set for a new decade
SLEEPING SINGULARITY
The furious past of our Galaxy's black hole
ROSETTA AT REST
ESA's historic comet landing mission ends

Enjoy our Premium App experience now available from

Download on the App Store | amazon apps Available on kindle fire | GET IT ON Google play | zinio™

BBC
Sky at Night
MAGAZINE

BBC Sky at Night MAGAZINE

LOTS OF WAYS TO ENJOY THE NIGHT SKY...

The Sky at Night

✦ Television

Watch The Sky at Night *TV show each month and get exclusive insight from the presenters*

BBC Sky at Night MAGAZINE
EASY ASTRO PHOTOGRAPHY
BACK GARDEN ASTRONOMY
WEEK
28 SEP – 04 OCT
The Summer Triangle
Iain, it's day one of Back Garden Astronomy Week!

◀ Back Garden Astronomy Week

Want to discover the night sky but don't know where to start? Sign up to our regular email events for no-nonsense stargazing advice

✦ Special issues

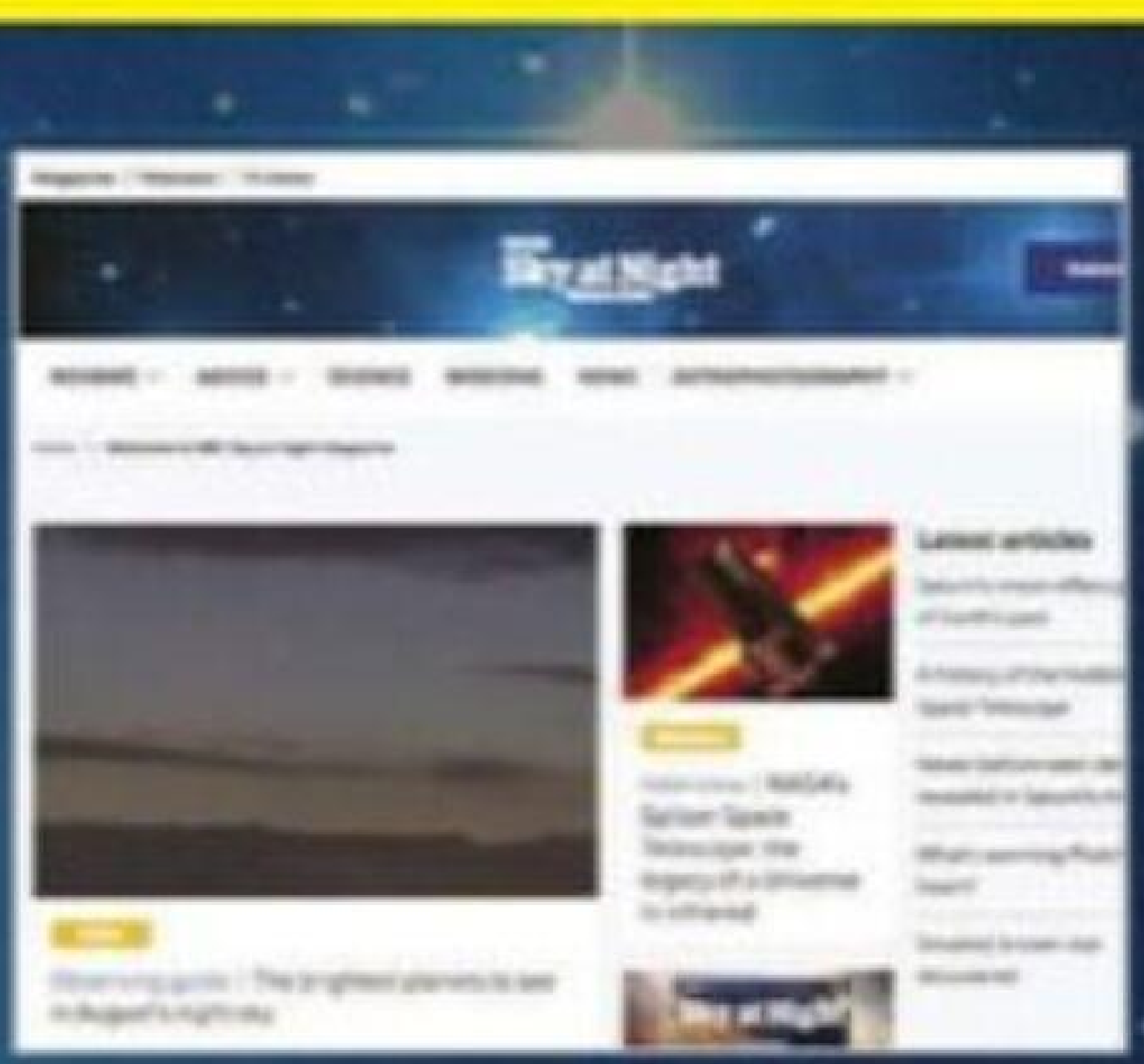
The Complete Guide ASTRO PHOTOGRAPHY
THE ASTRONOMER'S YEARBOOK 2020
THE APOLLO STORY

Delve deeper into observing, astrophotography and space exploration with our long reads

Issue 173, October 2019 ON SALE NOW!

▲ Social media

Follow on Twitter and Facebook to get essential news and website updates



▲ Online

Visit our website for the latest reviews, observing guides and expert advice

✦ Digital editions

BBC Sky at Night
CELESTIAL FIREWORKS
Discover the top supernova remnants in the night sky this month
PLANETARY PERSPECTIVE

Read each issue on phone or tablet with Android or iOS apps

BBC Sky at Night MAGAZINE
RADIO ASTRONOMY

▲ Podcasts

Listen in to the magazine team and guests discuss the latest astro news

Sky at Night MAGAZINE
Highlights for the week ahead, 21–27 October

▲ eNewsletters

Top targets to observe each week, delivered straight to your inbox

Discover more at **www.skyatnightmagazine.com**